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CRITERIA FOR A STATE-OF-THE-ART VISION TEST SYSTEM

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FOR THE COMMANDER

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Many vision test/screening devices used in the Armed Services have not changed since the 1940's. The reduction in the size of the pool of "qualified" aircrew candidates has caused operational Commands to question the validity of these tests. Current objectives of vision testing have evolved from a means to eliminate pilot candidates to methods of predicting aircrew performance. The Naval Aerospace Medical Research Laboratory (NAMRL) is attempting to correlate the results of several vision tests with the visual abilities of pilot trainees as demonstrated during monitored training flights. This report describes status that could be considered as useful parameters for testing in the Armed Forces vision test battery of the future. One major conclusion is that the operational visual task(s) must be suitably described in order to select appropriate clinical and laboratory test measures. Correlations and validation studies can then be performed with cooperative efforts such as those between NAMRL and AFAMRL. Additional keywords: visual acuity; eye position measures; accommodation; neurology; color vision.

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PREFACE

Present military visual standards have existed with little real change since WWII. The design of instruments used to measure visual acuity, color vision, and muscle balance in military clinical settings remains unchanged since the original purchases over 40 years ago. As the pool of available and qualified enlistees decreases, operational concern about the basis and relevance of current visual standards increases.

The Naval Aerospace Medical Research Laboratory (NAMRL), Pensacola Florida, is currently investigating the correlations between aircrew (pilot) performance, as measured during operationally oriented flying training missions, and scores obtained on several vision tests. The final objective is to produce a validated and relevant series of vision tests that indeed test those factors necessary or useful during air combat, contribute to the success of the mission, and help insure the survivability of the pilot. In addition to recomended test methodologies, this effort will also define preferred standards of performance on the basic vision tests.

NAMRL has funded the Air Force Aerospace Medical Research Laboratory (AFAMRL) first, to design and construct a prototype automated vision tester, and second, to investigate current or state-of-the-art vision tests for possible inclusion in a second-generation automated vision testing system. This report fulfills the latter of these two tasks.

After an investigation of both the flight data and results of vision tests, and a determination of which vision tests are most appropriate as predictors of pilot performance, we hope to cooperatively decide on the methodology of administration of the vision tests, and the standard to which the aircrew member will be compared. We then envision a biservice, cooperative effort to construct and validate a new vision testing system for USN

and USAF medical facilities. This document is one step in that process.

The report was prepared by Systems Research Laboratories, Inc. (SRL), 2800 Indian Ripple Road, Dayton, Ohio 45440, under Contract F33615-82-C-0511. The work was performed in support of the Automated Vision Testing project for the Air Force Aerospace Medical Research Laboratory (AFAMRL), Human Engineering Division (HE), Wright-Patterson Air Force Base, Ohio 45433.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

INTRODUCTION

Historically, the number and variety of eye tests have not proliferated significantly over the years. Although occasional new tests are proposed, there are relatively few that have survived the rigors of clinical application or professional acceptance. Most clinical tests of any particular visual function appear to be based on similar foundations, and acceptability of these tests may be associated with their ease of administration and historical precedent.

Perhaps the basis of this observation lies in the evolution of optometric testing itself. Historically, the patient has seen the eye specialist with complaints of diminished visual acuity (reduced ability to read written material) at either far or near distances, diplopia (double vision), or asthenopia (eye discomfort). Ophthalmic tests have been devised to measure the degradation in legibility of letters or similar optotypes, and to determine the relative position of the lines of sight in relation to the material being read.

Corrective devices typically included lenses to improve retinal focus and prisms (or exercises) to realign the lines of sight. In most nonpathologic cases, the symptom (blurred words or double vision) was alleviated, and the patient remained satisfied until his refractive error or muscle balance changed.

As the demands on our visual systems increased, more and more patients were seen by eye practitioners, and more sophisticated methods were used to address the same symptoms. Several groups of practitioners codified their methodology and established standards of performance -- all associated with legibility of written material. Standards evolved which set "perfect" acuity as 20/20, and "perfect" muscle balance as orthophoria.

Today, critical and exacting visual perception is required not only in reading print of various sizes, but in the entire gamut of visual detection, recognition, tracking, and higher cortical information processing. Perhaps one of the most critical and exacting series of visual tasks today is required of military aircraft pilots. It is truly a survival advantage to be able to detect, identify, and track both friendly and enemy aircraft infringing on one's airspace.

Although the uses to which pilots' eyes are put may have taken a quantum jump when compared to Abe Lincoln reading books by firelight, the tests of visual function have not kept pace with these uses. Most clinical tests are still based on legibility of optotypes or gratings (none of which shoot back), or of muscle balance under artificially controlled conditions. This is not to say that these tests are no longer valid; but it is extremely difficult to defend many of them in light of the extreme differences in stimulus conditions presented to the patient when in the eye clinic and when in the cockpit.

Aircrew selection today is partially dependent on eye tests recommended during the 1940s. Other than changing the number of letters to read on the 20/20 line, or the absolute value of a phoria test or two, standards for pilots and navigators have remained unchanged since that time. In the wider sense, these standards may be readily used to reduce the number of candidates to an administratively manageable number; but there is little data to show how pilot performance is affected by relatively small changes in vision as measured by current tests. In addition, as the pool of available and motivated candidates decreases, military selection procedures must be modified to include tests that will indeed predict the visual performance of aircrew much more accurately than do currently used tests.

This report is a description of many currently used vision tests, employed in clinical or research environments. No

attempt is made to correlate performance on these tests to aircrew suitability or performance. The tests are enumerated for possible inclusion in a battery of candidate vision tests to be statistically examined for validity as predictors of aircrew visual performance. The collection is not all-encompassing. Several tests have been omitted because they did not meet the criteria of size, time, or information content established by the authors. Other tests have been omitted because of a lack of readily available information. Most of the included tests have been shown to be effective measures of visual performance under clinical or laboratory conditions.

We believe that one basis for a "good" visual test is its applicability to a specific visual task performed in the "real world." This selection can be made only after the visual tasks of the aircrew member are appropriately identified, and the limits of performance defined. Alternatively, the entire existing battery (or an intelligently derived subset thereof) of vision tests may be given to a series of individuals, and statistical tests may be used to determine which visual functions are of higher value to performance and survival.

An effective fighter pilot need not read the tail number on an enemy aircraft, nor will he be shot down by a sine wave, but he must be able to detect, identify, and track distant objects within his airspace. He must also be able to read written or printed instructions, interpret various in-cockpit video displays (both mono- and polychromatic), and gather data from round-dial instruments and indicator lights. If his aircraft is relatively advanced, he must integrate binocular or monocular visual data presented by his Head-Up Display (HUD) or Helmet-Mounted Display (HMD) with his perceptions of the outside world, as influenced by the optics of his canopy or windscreen. The visual environment of the cockpit and surrounding airspace will vary from extremely bright (10^8 millilamberts) to extremely dim (10^{-6} millilamberts), with a wide gamut of contrasts and

motion cues. This total environment will not be duplicated in eye clinics in the foreseeable future. Hopefully, clinical tests will be produced that effectively predict man's performance under these extreme requirements.

VISUAL ACUITY

Although the term "visual acuity" is commonly interpreted to mean the level of clarity of an image, this defines only one type of acuity measurement. Generally, visual acuity may be divided into several categories.

1. Detection acuity or "minimum detectable": The smallest size (angular subtense) of a spot at detection for given conditions of ambient illumination and contrast.

2. Separation acuity or "minimum separable": The smallest separation (again, in angular subtense, and for limited conditions) at which two spots or lines can be identified as two rather than one.

3. Resolution acuity or "minimum resolvable": The smallest angular size of a target such as a Landolt C, Tumbling E, Tribar, etc., at which it can be recognized or its orientation identified.

4. Form vision: A common acuity test performed in eye clinics, involving the recognition and identification of alphanumerics or other pictorial targets.

Special types of acuity may also be defined, such as vernier acuity, the minimum disparity between the ends of two line segments at which a displacement or misalignment can be recognized; stereoacuity, the minimum (relative) retinal displacement of a portion of an image, which causes that portion to appear to be at a different depth from the rest of the scene; or contrast sensitivity, the minimum contrast of a target required for detection.

Which measure of acuity is chosen depends on the function under investigation. Although there is some correlation among

SPOT DETECTION

Detection of spots refers to the discrimination of low contrast, small targets as compared to visual acuity, which requires the resolution of a high-contrast pattern; or contrast sensitivity, which involves the detection of a spatially-extended grating. Because of the low contrast and small spatial extent, spot detection may be better correlated with real-world tasks such as the visual detection of distant aircraft.

Overington (1976) summarizes a number of visual detection studies and provides threshold data relative to target size, temporal duration, background luminance, aspect ratio, focus, and retinal location. Baumgardt (1972) has pointed out some problems with obtaining absolute thresholds, the smallest amount of light that can be seen. These problems include the need for extensive dark adaptation, the critical nature of the observer's response criterion, the stochastic nature of a light source, and the sensitivity of the threshold to mild stimulants such as caffeine and nicotine. These problems can be alleviated when the target is presented in a photopic environment.

In a photopic environment, the sensitivity for detection is greatest at the fovea and decreases with retinal eccentricity (Johnson, Keltner, and Balestrery, 1978; Lie, 1980). Adams, Haegersrom-Portnoy, Brown, and Jampolsky (1984) have argued that foveal spot detection and acuity are closely related. They hold that the difference between an "O" and a "C" involves the contrast change at the gap in the "C." Foveal spot detection should thus positively correlate with measures of acuity.

Instrumentation and Methodology

Spot detection is usually considered the 50% probability-of-seeing threshold, with the time and location of presentation being known to the observer. The typical procedure is to slowly

The Ideal Instrument

One approach to designing the ideal test of dynamic visual acuity would be to identify the real-world tasks that are of interest. If the tasks tend to involve extended target exposures and eye movements then the selected dynamic visual acuity test should include these factors. The correlations between dynamic visual acuity and dynamic tasks tend to be higher than between static acuity and dynamic tasks. Nevertheless, it is not possible to predict on an _a priori_ basis what specific tasks will realize significant correlations. If possible, the selected test should be extensively validated.

No one dynamic visual acuity task reported in the literature appears to have a distinct advantage. Only two factors appear to be a firm requirement. First, the range of velocities should extend from 0 deg/s up to about 140 deg/s. Incrementing in 20 deg/s steps appears to be adquate resolution. Second, the critical detail of Tumbling-E or Landolt-C targets should range from 0.5 to 10 minutes of arc. This range should accommodate the degradation of performance with increased velocity.

A test is envisioned where the observer would indicate the orientation of a Tumbling-E or Landolt-C target that is in continuous motion. The target would smoothly transition through a sequence of velocities and target sizes until an acuity measurement was achieved for each velocity.

If target motion is achieved by having observers view a rotating mirror, it should be recognized that the virtual image does not move at twice the angular rate of the mirror (Goodson, 1979). Rather, the relationship is nonlinear and depends upon the distances from the center of rotation of the mirror to the observer and the target and upon the closed angle formed by the observer, mirror, and target.

A pair of mirrors mounted in the X and Y axes allow for two-dimensional target movement. Furthermore, current technology allows high velocities and bidirectional movement. For example, a target could be oscillated or moved in a circle. General Scanning manufactures galvanometer driven mirrrors and analog controllers that can be used to generate target motion. The G325DCT scanner has a maximum optical deflection of $\pm$20 deg and a bandwidth of dc to 150 Hz in X and and 120 Hz in Y at the -3 dB points. The dimensions of the mirrors and galvonometers are approximately 10 x 10 x 15 cm and each electronic unit is approximately 48 x 9 x 18 cm.

General Scanning galvanometers have also been incorporated into a visual stimulus deflector by the Stanford Reseach Institute (Crane and Clark, 1978). This device allows a range of movement of 40 deg horizontally and 30 deg vertically and 15 diopters (D) in depth. The target is viewed through a variable pupil. The focal length (f) is 50 mm. The device has a time delay of 1 msec, a resolution of 10 sec of arc, and a response from dc to 200 Hz. Two General Scanning CCX-101 amplifiers are used to drive the G300PD Optical Scanners. Gain and offset controls plus angular postion are available. The optics are approximately 40 x 15 x 10 cm and the electronic controller is approximately 48 x 9 x 18 cm. The cost is approximately $10,000.

velocities. For example, there was an increase from about 2.3 to 9.0 minutes of arc with an age shift from 16 to 80 years for a target moving at 150 deg/s.

In general, dynamic visual acuity is a complex visual phenomenon that is probably dependent on both position and velocity errors on the retina. In addition, dynamic visual acuity is distinct from static acuity in that static acuity is an inconsistent predictor of dynamic visual acuity, and factors such as illumination and eccentricity have a different effect on each measure.

Methodology and Instrumentation

Dynamic tests of vision such as dynamic visual acuity are generally not included in a clinical examination due to refraction being based on static tests, the difficulty and expense that such a test would involve, and uncertainty about interpretation. There is no standardized dynamic visual acuity test. In fact, dynamic visual acuity takes on very different meanings for different researchers. For example, tasks have varied on their requirement for eye and head movements and have used exposure durations ranging from instantaneous to extended.

Burg (1975) describes an apparatus for testing dynamic visual acuity. Basically, a slide projector was mounted on a motor-driven turntable that was positioned above the observer's head. This system is large and bulky because of the large projection screen that is required.

Most laboratory experiments of dynamic visual acuity (e.g., Brown, 1972a, 1972b; Ludvigh and Miller, 1958; Miller, 1958) have achieved target motion by rotating a single mirror. Ludvigh and Miller had observers directly view the mirror's reflection. In all of these studies, Landolt C's served as targets.

while the target was moved horizontally across the visual field at various eccentricities for 180 msec. Using moderate target velocities not exceeding 50 deg/s, Brown found that dynamic visual acuity was generally a linear function of velocity with the slope decreasing for larger eccentricities. The exception was for slowly moving targets (5 deg/sec) in the periphery. This combination of conditions actually improved acuity when compared to the static case.

When Brown instructed his observers to track the target with pursuit eye movements, dynamic visual acuity was again found to be approximately a linear function of target velocity. Eye movement recordings revealed that observers were making a series of saccadic movements to acquire the target and then smoothly tracking. The latencies of these saccades were found to decrease with increasing target velocity. In contrast, the velocity error of the eye (eye velocity minus target velocity) during the final smooth movement increased with target velocity, resulting in an error in retinal position.

Once a moderate level of illumination is reached, static acuity remains relatively constant. In contrast, dynamic visual acuity improves with illumination over a wide range of values (Miller, 1958). The greater the target velocity, the more dynamic visual acuity improves with relatively high levels of illumination. Similarly, limiting the illuminated area surrounding the moving target has been found to have essentially no effect at 20 deg/s, but a profound, negative effect at 110 deg/s (Goodson and Morrison, 1981a).

Both static acuity and dynamic visual acuity decrease with increasing age. For example, Burg (1966) reported that the size of the smallest critical detail that could be resolved increased from about 0.9 to 1.6 minutes of arc with an age shift from 16 to 80 years. In comparison, the decline of dynamic visual acuity with age becomes extremely pronounced with high target

The duration of the target exposure is a critical factor for dynamic visual acuity. Elkin (1962) found that degradation of dynamic visual acuity with increasing velocity was accelerated by limiting the exposure time. Similarly, dynamic visual acuity performance benefited from increased anticipation of target onset.

A critical finding by Ludvigh and Miller was that even though observers were selected for a static acuity of 20/20 or better, substantial individual differences were found for dynamic visual acuity. In fact, the correlation between the a and b components of the dynamic visual acuity equation was not significantly different from zero. Low but significant correlations between dynamic visual acuity and static acuity were reported by Burg and Hulbert (1959, 1961). These correlation coefficients tended to decrease with target velocity and to be higher with a brief exposure duration rather than an extended exposure static target. Dynamic visual acuity was found by Shinar, Mayer, and Treat (cited in Sekuler, Tynan, and Kennedy, 1981) to be related to other vision tests only when motion was involved in the other vision tests.

In contrast to the low correlations typically found between dynamic visual acuity and static acuity, Burg (1966) reported moderate correlations ($\underline{r}$ = +0.35 to +0.71) at velocities ranging from 60 deg/s to 150 deg/s. This study is unique in that a wide age range was sampled (16 to over 80 years), both males and females were used, there were a wide range of static acuities (20/13 to 20/200), and the sample size was extremely large (N = 17,500).

One problem with the Ludvigh and Miller findings is that the extent to which pursuit eye movements were involved is not clear. Brown (1972 a,b) conducted a series of experiments in which eye movements were either not allowed or were allowed and recorded. In one study, observers fixated a central marker

DYNAMIC VISUAL ACUITY

Many visual tasks involving airborne or ground-based vehicles require the discrimination of a moving target by a stationary observer, or of a stationary target by an observer who is in motion. Dynamic visual acuity refers to visual discrimination performance when there is relative movement between the observer and the target. Goodson and Morrison (1980a) and Hoffman, Rouse, and Ryan (1981) cite several studies to demonstrate that dynamic visual acuity is a good predictor of a number of real world dynamic tasks. For example, piloting performance and vehicle driving records have been shown to significantly correlate with dynamic visual acuity, usually to greater extent than static acuity.

The typical dynamic visual acuity task requires a stationary observer to view a smoothly moving target. In general, the size of the smallest detail that can be resolved increases with the velocity of the target. In an early study of dynamic visual acuity, Ludvigh and Miller (1958) asked observers to discriminate the orientation of a Landolt C that moved horizontally and was visible for 0.4 s. These data were described by the equation

$$\text{dynamic visual acuity} = a + bx^3$$

where a = static acuity, and
b = the loss of acuity with increasing target velocity.

In a subsequent study, Miller (1958) found that this equation adequately described the results whether the target moved in the horizontal or vertical planes and whether the target or observer was in motion.

sequence begins with a large target that is reduced in relatively large steps until two incorrect responses are recorded. At this point, target size is adjusted in small steps until a threshold is reached. This system was found to be in good agreement with a standard projection chart for high-contrast targets. This agreement was best for good acuities (20/40 or better). Target contrasts of 99, 20, and 5% were selected for inclusion in clinical testing.

Several acuity tests are available that use convex lenses and prisms to simulate distant vision. For example, the Keystone Telebinocular tester uses a Landolt-C test with a range of 20/200 to 20/15. The test may be monocular or binocular and may be conducted at a near (2.5 D) or far (optical infinity) point. Similarly the Bausch and Lomb IVEX (Integrated Visual Examination System) provides near and far tests of acuity using Tumbling-E and Snellen targets ranging from 20/400 to 20/15. The far test may be monocular or binocular.

Ideal Device

The ideal instrument for measuring form vision or "letter acuity" would be capable of displaying high-quality negative-contrast targets at a near point and at optical infinity, to obtain a precise psychophysical threshold using a staircase-type procedure, and be capable of measuring the acuity for either Landolt-C or Tumbling-E targets from 20/200 to 20/10. As an extension to most clinical tests, both isolated and crowded targets should be included. In addition, a range of target contrasts should be provided. Since vernier acuity appears to be a unique process, a separate vernier acuity test should be included with a range of 1 to 100 sec of arc.

7. Acuity improves with the luminance of the surround.

8. Acuity is dependent on the light and dark adaptation state of the observer.

9. Optimum acuity is found with a pupil size of approximately 2.4 mm.

10. Acuity declines with refractive error.

11. Males have been shown to have better acuity than females.

12. There is some evidence that acuity improves with distant viewing, although the literature is conflicting.

Methodology and Instrumentation

A relatively large number of wall chart variations are available from optometry supply companies. These charts include Snellen letters, Landolt C's, and Tumbling E's and typically range from 20/400 to 20/10 at a distance of 20 feet (6.1 m).

The Baylor Visual Acuity Tester (BVAT) is a video version of the wall chart. Snellen letters or Tumbling E's are displayed singly or in lines, in sizes ranging from 20/400 to 20/10 and can be used at either 10 or 20 feet (3.05 or 6.1 m). Targets may have negative (dark target on light background) or positive (light target on dark background) contrast.

Mainster et al. (1981) describe an automated acuity tester that allows for variable target contrast. Tumbling E targets are displayed on a television monitor. The observer uses a remote response box to control a computer-generated, four-alternative, staircase presentation procedure. Each trial

all objects under adverse conditions such as rain and fog have low contrasts and fuzzy edges. It is unlikely that standard acuity tests can predict the resolution of many types of targets under many conditions. As a remedy, the use of low-contrast acuity targets has been recommended (Mainster, Timberlake, and Schepens, 1981). See also the discussion on Gaussian targets later in this section.

The techniques discussed to this point can all be considered subjective in that they are based on the judgments of the observer. Several objective techniques have been devised, primarily involving oscillatory devices, optokinetic nystagmus, and arresting nystagmus (Borish, 1975; Newman, 1975). Checkerboard or striped patterns are oscillated or rotated, and the smallest pattern size that elicits the appropriate eye movement is assummed to correspond to the acuity of the observer.

A number of target and observer variables affect visual acuity (e.g., Burg and Hulbert, 1961; Newman, 1975; Riggs, 1965; Uttal, 1981; Westheimer, 1965, 1972a). Briefly:

1. Acuity improves with target luminosity and contrast.

2. Acuity improves with the duration of the exposure.

3. Acuity is best with horizontal and vertical orientations and declines with those that are oblique.

4. Wavelength affects acuity, depending on the chromatic adaptive state of the observer.

5. Acuity declines with eccentricity.

6. Acuity is independent of low velocities (less than four deg/s).

recognized. The Snellen fraction is frequently converted to a decimal.

An equally large number of progression schemes have been proposed. The typical technique is to start with a large target or line of targets and progress downwards in size until recognition fails. The smallest target recognized or resolved is the acuity of the observer. Arithmetic, geometric, and logarithmic progressions have been suggested with no one progression being clearly favored (Borish, 1975), although the NRC recommends log progressions.

Another issue is the number of letters to include on a single line (Ferris, Kassoff, Bresnick, and Bailey, 1982). Given that more letters can fit on a line of smaller visual angle, the criterion for determining acuity becomes inexact. In addition, acuity targets that are close together may interact and reduce acuity performance, particularly for amblyopes. This phenomenon has been referred to as crowding. Crowded targets may be most representative of a task such as reading, while uncrowded targets may be most applicable to predicting aircraft or ship identification. A general guideline for the prevention of crowding is to separate individual letters on all sides by a space equivalent to at least one letter.

Borish also cites a number of standard practices for testing acuity. In general, the test chart should have high contrast targets (greater than 80%), maintain adequate separation of letters or targets on a line, test at a distance of either 20 feet (6.1m) for far point or .5 m for near point, and consider acuity as corresponding to that line of targets on which more than 50% are correctly recognized or resolved.

One criticism of standard acuity tests is that they only employ high-contrast targets. Many objects, such as distant aircraft, always have relatively low contrasts, and virtually

double bars and dots, and vernier lines. The Landolt C is a circle with a gap such that both the gap width and the stroke width equal 1/5 the outer diameter of the circle. The stroke width of a Tumbling E is also 1/5 the vertical or horizontal dimension. For the Landolt-C target, the best visual acuity is approximately 0.4 minutes of arc (Shlaer, 1937).

Vernier acuity is similar to detection acuity for lines in that the threshold for each is extremely small. The minimum discriminable misalignment of two vernier lines approaches 1.0 second of arc, which seemingly exceeds the limits of receptor density on the retina. It is evident that both detection and vernier acuity involve unique processes. Organization in the central nervous system is probably responsible for the high level of acuity achieved when stimuli consist of extended lines.

Borish (1975) describes a large number of variations of each acuity test involving various letter choices and forms. The main drawback to the use of Snellen letters is that letters differ in their recognizability. Various sets of letters of roughly equal legibility have been assembled. The advantage of the Landolt-C or Tumbling-E optotypes is that they only vary in orientation. This is perhaps why the National Research Council recommends the use of Landolt Cs as test targets. Numerals have also been used to test acuity, although they vary widely in legibility (Penn, 1981).

Accompanying the large number of acuity tests for both clinical and experimental use are a large number of expressions of acuity. The two most widely cited measurements are the Snellen fraction and the threshold in minutes of arc. The Snellen fraction is the distance at which the test is conducted divided by the distance at which the smallest stroke-width recognized subtends 1 minute of arc. If the test is conducted at 20 feet (6.1m), then an acuity of 20/20 indicates that a character with a stroke-width of 1 minute was successfully

STATIC VISUAL ACUITY

Although there has been discussion concerning the replacement of acuity with tests of contrast sensitivity using sinusoidal gratings as targets, there are distinct reasons for the validity of visual acuity as a unique measure of the spatial resolving power of the visual system. Westheimer (1972b) makes the point that the response to a grating tells us something about the properties of a large receiving surface, whereas the recognition of a letter provides information specific to the stimulation of a small and well defined region. There is reason to suspect that each measure taps separate but overlapping visual processes to the extent that the retention of both tests is warranted.

Acuity tests can be divided into those involving detection, recognition, and resolution. Examples of detection acuity include the detection of a spot or a line. Ricco's Law states that there is no lower limit to the size of a spot that is detectable. For small targets, detection is dependent on the reciprocal relationship between the intensity and area of the target such that intensity multiplied by area is a constant. Similarly, extremely small thresholds have been reported for line detection. For example, Hecht and Minte (1939) found that a black line subtending 0.5 minutes of arc on a white background could be detected 50% of the time.

Line detection performance can be contrasted with the standard Snellen chart where the task is to recognize letters of the alphabet. The limit of performance corresponds to a stroke width of approximately 0.5 minutes of arc (20/10) with recognition of a 1.0 minute width (20/20) considered clinically adequate.

Several resolution tests of acuity have been devised. These include Landolt rings or C's, Tumbling E's, checkerboards,

the various tests, the ability to predict performance on one type of VA test by the results on another is chancey at best. If the pilot's visual requirements include the ability to discern a small, low-contrast, often blurred target at optical infinity, the visual test method should emulate this condition as closely as possible. If the requirement is to be able to read tail numbers, dial legends, or CRT calligraphics, then the test should emulate this condition. In general, a very poor score on a Snellen acuity test indicates a degraded ability to detect and recognize distant targets. However, there appears to be little if any correlation between small differences in the ability to recognize various letters, and the ability to detect an intruder in one's airspace.

increase the contrast or size of a static target until the observer indicates detection. Using a positive contrast target (light target on a dark background), contrast or luminance can be varied with a neutral-density wedge or by using an LED.

Adams et al. offer a test of spot detection that is easily understood and performed by the observer. It is rapid, correlates well between optometrist and technician examiners (r = +0.88), has high test-retest reliability (r = +0.83 to +0.85), and has a moderate correlation with letter acuity (r = +0.75). The observer visually tracks a spot of light that horizontally moves back and forth. The contrast of the test spot slowly decreases until it is no longer visible. The observer indicates the visibility threshold by pushing a button.

This instrument has been developed and patented by Optical Sciences Group, Visual Sciences Division. The device consists of a bank of 16 LEDs that are sequentially illuminated, appearing as a smoothly moving spot to the observer. The LEDs are spaced so as to provide sinusoidal motion with a total amplitude of 20 deg of arc. The frequency is 0.4 c/sec and the background luminance is 27 cd/m^2 (90 ftL).

Although this test does not require a moving target, motion allows the observer's threshold to be verified with eye movement recordings. That is, smooth pursuit eye movements will cease when the target is no longer visible. In addition, a moving target may make the task more interesting for the observer and may enhance the distinction between a target that is, or is not, visible.

Ideal Device

The Adams et al. test appears to be a good one, with several qualifications. First, a chromatically broadband rather than narrowband target should be used. A narrowband target such

as an LED is not representative of a real-world target, will reflect the chromatic sensitivity of the observer, and may produce misleading results due to chromatic aberration. Second, there is the question whether the target should be placed at a specific distance or in best focus for the observer. Although not mentioned, the display used by Adams et al. appears to be at an intermediate distance. The ideal test should produce results comparable with tests of both acuity and contrast sensitivity and should, therefore, be conducted at a distance, preferably optical infinity. Ambient conditions should be photopic and peripheral texture available in order to facilitate accurate focus.

A motor-driven mirror could be used to translate the target. A more elaborate device would involve a single SRI three-dimensional focus stimulator (Crane and Clark, 1978) for a monocular spot detection test or a pair of stimulators for a binocular test. Horizontal mirror movement of the stimulator(s) would smoothly translate a single target across the visual field. Adjustment of the focus stage(s) would position the target at optical infinity.

STEREOPSIS AND STEREOACUITY

The perception of objects or texture in depth appears to involve at least six visual cues, only two of which are binocular (convergence and stereopsis). In spite of this discrepancy, tests of stereopsis are the only common clinical tests of "depth perception." Although some individuals hold the opinion that stereopsis is active only for viewing distances of less than six meters, this assumption is untrue. Stereoscopic depth can be perceived at a much farther distance. The utility of stereopsis as a visual cue for perception of depth during flight is argumentative.

Stereopsis refers to the perception of depth when there are slight disparities between the retinal images of each eye. The development of random dot stereograms by Julesz (e.g., 1960, 1978) demonstrated that this phenomenon occurs in the absence of any monocular cues to depth. Recent evidence discussed by Uttal (1981) suggests that stereopsis is not merely a result of fusion or suppression of the disparate images, but rather involves the extraction of spatial invariances. Reviews of the stereopsis literature have been written by Gulick and Lawson (1976), Julesz (1971, 1978), Kaufman (1974), and Uttal (1981).

Stereopsis can be demonstrated with simple displays consisting of two lines or with computer-generated random-dot stereograms. The use of mirrors, prisms, polarizing filters, or color filters all allow dichoptic viewing in which each eye sees a unique part of the display. Stereopsis is achieved by spatially shifting a subset of the display for only one eye. In the case of the two-line display, the fused image results in the perception of a line that is either in front of or behind the surface of the display. For a stereogram, that part of the pattern which is disparate will appear at a different depth than the rest of the display. Monocular viewing, or binocular

viewing of the display without fusion, will not result in the perception of depth.

The experience of stereopsis depends on a slight disparity between the retinal images. Beyond a certain disparity, double vision or diplopia occurs. That disparity which allows fusion and singleness of vision is referred to as Panum's area. A large range of values have been reported for Panum's area. For example, Fender and Julesz (1967) found that for increasing disparity of a random dot stereogram, a value of two degrees was reached before diplopia occurred. In contrast, reducing the disparity did not result in fusion until the disparity was only a few minutes of arc. Characteristics of the observer, training, the criterion for diplopia, stimulus duration, surrounding stimuli, and stereoscopic depth have also been shown to have relatively large effects on the diplopia threshold (Duwaer and van der Brink, 1981; Warren, Genco, and Connon, 1984).

The smallest disparity for which two objects are seen in depth is termed stereoscopic acuity or stereoacuity. "Normal" stereoacuity requires that all of the optical, neural, and motor components in both eyes be in working order (Simons and Reinecke, 1974). Gulick and Lawson (1976) cite several examples of stereoacuity thresholds at or below 2 sec of arc for extended duration displays. This is an order of magnitude smaller than the diameter of a typical photoreceptor. When brief exposures are used, this threshold increases to 20 to 40 sec of arc.

Gulick and Lawson also discuss the similarities between stereoscopic acuity and visual acuity. These two measures of vision are positively correlated, especially for individuals with visual acuities of 20/20 or better. Both types of acuity are similarly degraded with retinal eccentricity and both have been found to improve with luminance. Stereopsis and stereoacuity are less sensitive to changes in high spatial frequencies and near-threshold luminances than is normal spatial

vision, and are most sensitive to vertically oriented stimuli (McKee, 1983; Wolfe and Held, 1983).

Disparity can be either crossed or uncrossed. If the left eye views the right line and the right eye views the left line of a two line display, disparity is crossed and the fused image will be of a single line that appears in front of the display surface. If each eye views the corresponding line, disparity is uncrossed and the resulting image will appear behind the display surface. There is evidence that crossed and uncrossed disparity thresholds are the result of separate processes in the visual system and that a crossed disparity results in lower threshold (Woo and Sillanpaa, 1979).

Given that convergence is symmetrical and the target is close to the line of sight, the depth signaled by a given disparity is given by the formula

$$\text{depth} = (.5I(\mathrm{TAN}(\mathrm{ATN}(D/.5I)+.5R)))-D$$

where I = interpupillary distance,
R = retinal disparity, and
D = fixation distance (Cormack, 1984).

When disparity is crossed, both R and the signaled depth become negative. As D increases, the signaled depth decreases.

A stereoanomaly or stereoblindness is the inability to perceive depth in a stereogram. Richards (1970, 1971) has divided stereoblindness into the inability to perceive crossed, uncrossed, and zero disparity. With zero disparity, the image appears on the surface of the display. Using brief presentations, Richards found that approximately 30% of his sample lacked at least one of the three disparity detectors.

In conducting tests of stereopsis, it is critical that eye movements not be allowed. Observers with either a crossed or uncrossed disparity deficit could shift their fixation in order to change the direction of the disparity. The typical technique used to prevent this is to use brief presentations. Unfortunately, some observers may require a relatively long viewing time to achieve stereopsis.

For example, Patterson and Fox (1984) tested 98 naive observers with random element stereograms. With brief exposures, 24 of the 98 observers were classified as stereoanomalous. When the 24 observers were subsequently tested using continuous viewing of the display, only 1 could be classified as stereoanomalous. Either the temporally extended display or the use of eye movements could have produced this result. The use of afterimages by Patterson and Fox allowed the presentation of an extended display but nullified the effect of eye movements. Of the 15 stereoanomalous observers tested, 12 correctly perceived the direction and magnitude of stereoscopic perceptions for both crossed and uncrossed disparities. This suggests that the neural mechanism necessary for stereopsis was intact in most of these "stereoanomalous" observers. What was required was a longer viewing time.

Complex random-dot stereograms require a considerably longer viewing time to achieve stereopsis than do either simple random-dot stereograms or several-line displays. The complexity of a stereo display is determined primarily by the number of disparity levels. This is clearly demonstrated in a comparison of Figures 3* and 6* in Julesz (1978). Figure 3* is a 1000 x 1000 element stereogram with approximately 100 levels of disparity. The fused image takes on the form of a hyperbolic paraboloid and a torus with a depth gradient. In contrast, Figure 6* is a 100 x 100 element display with only a single level of disparity. The resulting fused image is of an elevated diamond at a uniform depth. Although the number of elements

composing the display determines the quality of the image, the complexity refers to the number of disparity levels. While at least several seconds of viewing time are required to fuse the complex stereogram, depth can be immediately seen in the simpler stereogram. With repeated trials, fusion of the complex stereogram becomes much faster.

Methodology and Instrumentation

The method used by Patterson and Fox to test for stereoanomalies involved Landolt-C targets configured in a random element stereogram. The Landolt C was relatively large with the gap subtending almost four degrees of arc. For each presentation, the observer made a forced-choice response, indicating the orientation of the gap. Chance performance would correspond to 25% with four orientations. This method gives a single index of performance corresponding to each category of disparity and could be extended to include a range of disparity magnitudes.

An example of the methodology used to measure stereoacuity is found in Fendick and Westheimer (1983). The outlines of two squares, four min of arc in length and separated by 10 min of arc, were foveally presented for 500 msec. The observers task was to indicate which square was nearer. After every 20 trials, the disparity was adjusted to converge on a threshold value.

A number of ingenious devices have been invented to investigate the phenomenon of stereopsis. The original stereoscope was devised by Wheatstone and Helioth (Kaufman, 1974). The use of diagonal mirrors allowed a separate display to be presented to each eye.

The Brewster stereoscope eliminates the need for mirrors and provides a separate collimated image to each eye (Kaufman, 1974). The half-lenses should be used with displays whose

center-to-center distance equals the interocular separation of the observer. The Keystone Telebinocular vision tester uses lenses to provide a test of stereopsis with a wide range of disparities. The observer is shown a drawing of a row of pegs in a box. For each pair of pegs, the observer is asked to indicate the one that appears closer in distance. Prisms or Fresnel lenses may also be used with a stereogram (see Julesz, 1960, for a demonstration). A single mirror may be used with a stereogram. The distance to each display is equal and should allow normal accommodation and convergence.

While the devices described above require two spatially separated displays, the anaglyph and polaroid approaches use a single combined display and filters to provide each eye with a unique display. A single projecter may also be used with Vectographic slides (Kaufman, 1974). Care should be taken in specifying the optical components for use with polarized light, as certain materials will tend to depolarize the light. Anaglyph system results may also be contaminated by effects of the eye's chromatic aberration (pseudo- or chromo-stereopsis).

Several clinical instruments use polarizing filters to obtain measures of stereopsis. The Titmus Stereo Test provides a gross screening test and two tests with gradations of disparity. The screening test is a stereogram of a housefly that requires a yes/no response. The graded tests use circles or animals that appear at various depths. The Randot Tests provide stereo tests ranging in disparity from 600 to 20 sec of arc.

The anaglyph is a stereogram where the single display is half red and half green. Placing a red filter before one eye and a green filter before the other allows each eye to view half of the display. A demonstration can be found in Julesz (1978). Normal color vision is required for this device. The T.N.O. Test is a commercially available set of plates based on the

anaglyph technique and provides Julesz random dot stereograms over a range of 480 to 15 sec of arc.

The anaglyph technique may also be electronically generated. Patterson and Fox (1984) describe an elaborate system where the red and green guns of a color monitor are directly modulated. Red and green random-dot displays are generated with a delay selectively introduced between their outputs to create the desired retinal disparity.

Both polaroid and anaglyph devices are not completely efficient and will pass some amount of noncorresponding light, referred to as crosstalk. This crosstalk has minimal consequences for the quality of the stereoscopic image. Kaufman (1974) makes the point that even relatively high levels of such crosstalk do not significantly impact the level of stereopsis.

Fagin and Griffin (1982) review nine common, commercially available tests of stereoacuity and provide a logarithmic scale of disparity for comparison purposes. The tests are: Bernell Reindeer Stereotest, Titmus Stereo Test, AO Vectographic Near Point Card #3, TNO Test for Stereovision, Random Dot "E" Stereotest, Verhoeff Stereopter, Keystone Visual Skills Slide DB6D - Test 7, AO Vectographic Project-O-Chart Slide for Children, and the Randot Stereotest. Several of the tests achieve a range of disparity by using a variable viewing distance. This is undesirable in that disparity is confounded with viewing distance. The remaining tests provide from four to 10 levels of disparity at a fixed viewing distance. All of the reviewed tests allow extended viewing. Fagin and Griffin also present formulae for calculating stereopsis (as a percentage) and stereoacuity (in sec of arc).

Borish (1975) describes several clinical instruments for the assessment of stereopsis. Most of these tests, such as the Howard-Dolman test, the Verhoeff stereopter, and the Hofstetter

Stereotest involve binocular viewing and require the observer to either align rods that vary in depth or to indicate which one is closest. The major problem with these tests is the presence of monocular cues to distance.

Ideal Methodology and Instrumentation

It is recommended that tests of stereoacuity be preceded by a quick screening test for fusion and stereopsis. The latter could be the Titmus Housefly or the Random Dot "E" Stereotest. Stereoacuity should be considered as a multi-dimensional measure of vision. Large differences may be found, dependent on the display duration and complexity, and the direction of the disparity. In addition, separate measures of, for example, brief and extended dispays or crossed and uncrossed disparities, are not necessarily correlated. A single measure of stereoacuity is not recommended because of the likelihood that it would prove misleading.

The ideal instrument should allow little if any crosstalk between the images presented to each eye. The range of crossed and uncrossed disparities should extend from 2 to 400 sec of arc in log increments at a fixed viewing distance. The range actually employed would depend on the test conditions. For example, smaller disparity levels would be required for extended as compared to brief displays. At least two levels of complexity should be provided in random-element stereograms. Random-element displays appear to be most effective at preventing monocular cues to depth. Provision should also be made for extended and brief presentations and the generation of afterimages.

CONTRAST SENSITIVITY

Contrast sensitivity is the reciprocal of the detection threshold for a sinusoidal grating. A sinusoidal grating appears as a series of dark and light bars in which the luminance profile varies sinusoidally. The spatial frequency of the grating is the number of dark-bar/light-bar pairs per degree of visual angle, and the contrast is defined as one-half of the difference between the maximum and minimum luminance, divided by the mean luminance.

The contrast sensitivity function is often compared to the measurement of acuity that involves the visibility of small, high-contrast symbols. Although it has been suggested that contrast sensitivity is a more valid test of vision than acuity, there are distinct reasons for retaining both measures. For example, contrast sensitivity provides information on the properties of a large receiving surface while acuity provides information about the stimulation of a small and well defined region (Westheimer, 1972).

The typical measurement procedure is to increase the contrast of the grating until the observer indicates that he can detect the dark and light bars. While most physical systems exhibit monotonically decreasing sensitivity as spatial frequency increases, the visual system is most sensitive to an intermediate spatial frequency of 2 to 5 cycles per degree (c/deg). The decrease in sensitivity to low spatial frequencies is due to neural processing rather than the optics of the eye.

Kelly (1975) has suggested that a minimum of seven bars is required in order to adequately simulate an infinitely extended surface. With fewer bars, sensitivity would decline. This becomes a critical consideration when low-frequency gratings are used. Van den Brink and Bilsen (1975) have disputed Kelly's suggestion, attributing his findings to improper focusing.

Given proper focusing, van den Brink and Bilsen found fewer than seven bars to be adequate.

Comerford (1983) discusses the sensitivity of the function to a variety of vision abnormalities. In some cases, acuity is "normal," but contrast sensitivity testing indicates the presence of a disorder. Contrast sensitivity can potentially provide information concerning the integrity of the cornea, lens, retina, optic nerve, and cortex. Of particular interest are those disorders that tend to be spatially global and/or frequency selective. Comerford also points out several problems with the use of contrast sensitivity as a clinical measure, including the lack of a standard methodology, the need for normative data, the variety of displays used to present gratings, and problems with defining and controlling the observer's criterion for detection.

Norms have recently been provided by Ginsburg, Evans, Cannon, Owsley, and Mulvanny (1984) who obtained contrast sensitivity functions from two relatively large samples (N = 125 and N = 140). The mean ages were 35.9 (SD = 12.8) and 38.6 (SD = 14.5). Both samples exhibited a peak at about four c/deg with positively skewed tails. Variability was found to be greatest at the lowest and highest frequencies.

Ginsburg has been the foremost proponent of using contrast sensitivity as a predictor of visual performance. Contrast sensitivity has been shown to predict certain target detection and recognition measures better than acuity in both simulator (Ginsburg, 1981; Ginsburg, Evans, Sekuler, and Harp, 1982) and field studies (Ginsburg and Easterly, 1983).

Methodology and Instrumentation

Sinusoidal gratings may be generated by optical, electronic, or photographic means. The latter two methods are

the most common. Electronic displays typically employ oscilloscopes or CRTs, frequently under computer control. Low spatial frequencies are typically of higher quality than high spatial frequencies on an electronic display. For a CRT, the raster pattern determines the highest spatial frequency that can be displayed.

The Nicolet Optronix is a complete contrast sensitivity tester based on the AIM-65 microcomputer and a CRT. The operator uses a keyboard to select the display distance (0.02 to 65 m), screen size (2.5 to 200 cm), lines per screen (100 to 3000), peak contrast (0.1 to 0.95 -- although linearity may be a problem above 0.60), method (Von Bekesy tracking or a single staircase, method of adjustment, method of increasing contrasts or limits), preview time (1 to 15 s), fullscale time -- the time required to go from zero to full contrast (5 to 120 s), and the information to include in the printout.

A low cost ($60 for parts) function generator that interfaces to a computer and a Tektronix 604 cathode ray oscilloscope is described by Durham and Illingworth (1981). A spatial frequency range of 0.25 to 20 c/deg is selectable for an observer seated 1 m from the display.

There has been some recent controversy over psychophysical methods for use in measuring the contrast sensitivity function. Bradley and Freeman (1982, 1984) have advocated a spatial two-alternative forced choice procedure. They demonstrated that this method results in less variability than the method of adjustment used by Ginsburg (e.g., Ginsburg, Evans, Cannon, and Fullenkamp, 1980). Ginsburg (e.g., Ginsburg, Bittner, Kennedy, and Haberson, 1983; Ginsburg and Cannon, 1984) has subsequently adopted an automated ascending method of limits procedure, which appears to result in less variablity than either the method of adjustment or Bekesy tracking, a staircase procedure. The ascending method of limits is probably the psychophysical

technique most often used to obtain a contrast sensitivity function.

Dobson and Davison (1980) and Wiley, Harding, Gribler, and Kirby (1984) have advocated the spatial bandwidth equalization (SBE) technique as being efficient and not susceptible to criterion shifts on the part of the observer. Basically, the observer is presented with a display that varies horizontally in spatial frequency and vertically in contrast. The screen is divided into several segments with vertical lines. The observer's task is, for each segment, to position a horizontal line such that the pattern above the horizontal line is visible while the pattern below the line is not. These researchers found reasonable agreement between the SBE and more conventional techniques, although the SBE technique showed increased sensitivity at low and high spatial frequencies. Wiley et al. provide block and circuit diagrams of a device for use with a CRT that generates gratings according to the SBE technique.

A set of sinusoidal grating photographic plates is commercially available (Arden, 1978; Woo and Prentice, 1983). Each 28 degree plate represents a spatial frequency that varies vertically in contrast. The examiner slowly uncovers the grating until the observer indicates detection. A score of 1 to 20 is assigned to the point at which detection is indicated. The Arden test is potentially valuable as a quick screening test. Limitations include the variable rate of uncovering the grating, the close viewing distance of 57 cm, and the maximum spatial frequency of only 6.2 c/deg.

Ginsburg (1984) describes a contrast sensitivity test chart. The chart consists of six rows of 3 inch (7.6 cm) diameter gratings with spatial frequencies of 1, 2, 4, 8, 16, and 24 c/deg at a viewing distance of 2 m. The eight gratings in each row range in contrast from 0 to above visual threshold in approximately 0.1 log unit steps. Gratings are tilted in one

substituted for the distant test line to provide a near test of lateral and vertical phoria. Emsley (1962) describes a vertical extension of the Von Graefe technique.

Borish is extremely cautious in prescribing the Von Graefe technique. Inaccurate accommodation, shifting focus or attention between the two images, the presence of edges in the periphery, and an insufficient number of repetitions may all bias the measurement of phoria. For all methods, Borish recommends the use of color filters to enhance dissociation.

The Maddox rod technique is a distortion test that uses a spot of light as a test target and creates dissociation by placing a glass rod or series of adjacent rods (strong cylindrical lenses adjusted so their axes are horizontal) before one eye. The resulting streak effectively prevents fusion. The use of a red Maddox rod further insures dissociation. A base-in or base-out prism placed before the other eye is adjusted until the streak passes through the spot of light. Adjusting base-up and base-down prisms with the other eye covered by a vertical Maddox Rod may similarly be used to measure vertical phoria. Variations of the Maddox rod technique include the Screen Maddox test. Essentially, brief exposures of the prism eye, each at a new prism setting, prevents cues due to target motion.

Maddox rods may also be used to measure cyclophoria (Wick and Ryan, 1982). Briefly, Maddox rods are placed in front of each eye and the resultant streaks are compared for parallelism. The apparent rotation of one image indicates the presence of cyclophoria.

Borish recommends that the Maddox rod technique should not be used for near testing. The primary reason is the inadequacy of a spot of light as a stimulus to accommodation. However, both red near point and white far-point Maddox-rod tests are available in the Bausch & Lomb IVEX System, an integrated vision

inaccurate or has large fluctuations, the accommodative-convergence linkage will produce ambiguous phoria measurements.

The literature relating phoria to visual performance and visual discomfort is often speculative and generally inadequate. There is some evidence that uncorrected heterophorias could lead to diplopia under conditions where cues for fusion are weak or absent, although the link to real world tasks is lacking. For example, Burg (cited in Henderson and Burg, 1970) conducted a large scale sample and failed to find a relationship between lateral phoria and driving performance. Emsley (1962) and Ogle (1968) have suggested that heterophoria may be associated with ocular discomfort, with vertical heterophoria having the largest effect.

Methodology and Instrumentation

Borish (1975) describes a number of techniques for measuring dissociated and associated phoria. The Von Graefe prism technique involves placing a base-in or base-out prism before one eye and a base-up or base-down prism before the other. For lateral phoria, the base-up or base-down prism is used to create diplopia and displace a line of distant test targets, providing dissociation. Heterophoria will be evident by the two images drifting apart in a lateral direction. The base-in or base-out prism in front of the other eye is then adjusted until the two images form a single vertical line. The final prism power that produces alignment is the dissociated phoria. The direction of the base indicates the type of phoria, base-in prism indicating exophoria and base-out prism indicating esophoria.

An analogous procedure is used to measure vertical phoria. The base-in or base-out prism is used to create dissociation and the base-up or base-down prism is adjusted until the targets form a single horizontal line. A near-point card can be

is related to lateral phoria, the two are not synonomous (Owens and Leibowitz, 1983).

Lateral phoria refers to the amount of base-in or base-out prism power required to laterally align dissociated images. Prism power is expressed in diopters; one prism diopter is a deviation of 1 cm at 1 m, or 0.573 deg of visual angle. Relative overconvergence by one eye is referred to as esofixation or esophoria and requires a base-out prism to achieve lateral alignment. Similarly, underconvergence is referred to as exofixation or exophoria and requires a base-in prism.

Vertical phoria refers to the amount of base-up or base-down prism power required to vertically align dissociated images. If a base-down prism over the right eye (or a base-up prism over the left eye) produces vertical alignment, the condition is referred to as right hyperphoria. Similarly, the requirement for a base-down prism over the left eye (or a base-up prism over the right eye) corresponds to left hyperphoria.

Cyclophoria is the latent tendency of the eyes to rotate in opposite directions about the line of sight. Incyclophoria is an upwards convergence of the primary vertical meridians and excyclophoria is a downwards convergence. Wick and Ryan (1982) discuss the frequency, cause, and symptoms particular to cyclophoria. The latter include the perceived tilting and shifting of objects and the head tilt that may accompany a change from distant to near fixation.

Tests of phoria may be conducted at near or far optical distances. Typically, a far test (at or close to optical infinity) is compared to a near test (at several diopters). It is critical that accommodation correspond to the distance of the display, especially for near testing. If accommodation is .cp2

MEASURES OF HETEROPHORIA

Heterophoria (sometimes abbreviated to "phoria") refers to the relative position of the eyes in the absence of fusion. This measure of binocular balance is frequently termed the resting position or tonic state of convergence. If the eyes are balanced and in correspondence when fusion is absent, the condition is termed orthophoria. More commonly, there is some amount of heterophoria, the tendency for the lines of sight to deviate in the absence of fusion. The implication is that fusional effort is required to fixate a target.

If fusion is completely absent, dissociated phoria is being measured. This measurement typically involves creating diplopia of one object, or presenting a separate image to each eye. The presence of some fusion results in the measure of associated phoria, essentially the nulling of fixation disparity with prisms, or the amount of fusional vergence not replaced by prism adaptation. The relationship of associated and dissociated phoria is a matter of some controversy although the former is typically 20 to 25% less than the latter (Schor, 1983). Schor attributes this discrepancy to prism adaptation.

The term "phoria" assumes that the observer is capable of binocular fusion. This is distinct from the condition of heterotropia, strabismus, or squint, where at least one eye deviates from the target during normal viewing conditions and fusion is never achieved. Dissociated phoria is considered distinct from associated phoria. The latter is actually a measure of fixation disparity (which will be discussed elsewhere in this report).

Although dissociated phoria is frequently referred to as tonic vergence or the resting position of vergence, these terms are more applicable to the measurement of vergence in the absence of texture--the dark vergence. While the dark vergence

and heterophorias. The methodology for this test is not standardized, and it is not in the battery of tests commonly given aircrew members.

Heterotropias are identified as being intermittent esotropia, exotropia, or hypertropia. If not identified, the condition is assumed to be constant. In addition, the deviating eye is identified when the condition is a heterotropia.

By definition, both orthophoric and heterophoric individuals are able to fixate both lines of sight on a target as long as the eyes remain unoccluded or associated. If, however, dissociation occurs because of fatigue, G-forces, or interruption of one eye's line of sight by obstructions within the cockpit, heterophoric individuals may lose fusion -- resulting in diplopia (seeing double) or suppression (turning off the vision in one eye) when the line of sight is reestablished. Individuals with large heterophorias are more likely to experience this problem than those with relatively small heterophorias.

Aircrew medical evaluation procedures establish maximum heterophoria values. No heterotropia is acceptable. There is usually no differentiation between suppression and diplopia produced by excessive eye muscle imbalance, even though suppression may be a viable and relatively innocuous alternative to single simultaneous binocular vision. Diplopia, on the other hand, is at least disturbing, and at worst debilitating.

Measures of heterophoria or heterotropia are commonly performed while the patient is looking straight ahead. Gross fusion testing is commonly done by the "red lens test," which is performed at the extremes of gaze. Although standards exist for heterophoria and heterotropia, failure of the red lens test merely indicates referral to an eye specialist for further evaluation.

Fixation disparity (sometimes called "retinal slip"), is a measure of the lines of sight while both eyes are associated. There appears to be a correlation between fixation disparity

EYE POSITION MEASURES

The position of each of our eyes is controlled by six extraocular muscles, which are controlled by three major cranial nerves. The twelve muscles interact in an extremely complex manner, in that the primary effects of each muscle dynamically change as the positions of the eyes change. For instance, the primary depressor of the eyes in one position is the inferior rectus (innervated by the 3rd cranial nerve), in another position it is the superior oblique (innervated by the 4th cranial nerve). Convergence of the eyes is primarily caused by the medial rectus (innervated by the 3rd cranial nerve), but its antagonist is the lateral rectus (innervated by the 6th cranial nerve).

Common aircrew vision tests include a method to determine the "resting position" of the eyes' lines of sight. If the lines of sight remain parallel when the vision of one eye is occluded or dissociated, the patient is said to possess "orthophoria." If the line of sight of the dissociated eye crosses that of the fixating eye, the patient is said to have an "eso" condition. If the line of sight of the dissociated eye diverges from parallelism, the patient is said to have an "exo" condition. If one line of sight is higher than the other, the patient is said to have a "hyper" condition.

Heterophorias are changes in eye position that occur only when an eye is covered or dissociated. Heterophorias are identified as esophoria, exophoria and hyperphoria as described above. There is no identification of which eye is heterophoric, since the dissociated eye (whichever one it is) undergoes a position change.

Heterotropias are more or less permanent changes in eye position. In this case, the lines of sight remain unaligned even when dissociation or occlusion is not present.

The Ideal Test

For airborne applications, a good color test would be one that would allow testing of the pilot's perception of tower and carrier signal lamps under daytime, nighttime, and fog conditions. Since color CRTs will be gaining popularity in military cockpits, a test based on legibility of characters and figures presented by these devices under typical environmental luminance conditions should also be considered. Cockpit warning signals are usually bright enough, and use redundant attention-getting mechanisms (bright red plus blinking), so individuals who pass either of the first two recommended tests should see the warning signal. If color contrast is important (as for airborne observers or photographic interpreters), a similar test using photographically prepared plates or dyes can be considered.

all combinations of eight neutral density filters and eight color wheel exposures for a total of 64 hue/luminance combinations.

Working Group 41, of the National Research Council's Committee on Vision, evaluated several types of color vision tests on the basis of reliability, validity, maintenance, calibration and administration. The Nagel Model I anomaloscope was used as the standard test of red-green color vision, and several other anomaloscopes were tested in conjunction with it. Pseudoisochromatic plate tests were compared to each other or to known valid or reliable plate tests. Farnsworth-Munsell 100-Hue and similar tests were also described, as were Holmgren wool tests. Several lantern tests were also evaluated, including the FALANT (a good general description of why the FALANT was chosen by the Navy is included). Most well-known tests rated high for validity and reliability.

Since the perception of color is dependent on (among many other factors) adaptation level of the eye and luminance of the target, it is reasonable to test color vision under extreme conditions. For carrier qualified pilots, testing under low mesopic general illumination might be indicated if color (rather than brightness) discrimination of the signal lights is important. A similar test might be envisioned for pilots flying aircraft equipped with color displays (color CRTs or moving map displays). Interesting tradeoffs will be found between maintaining optimum dark adaptation and perception of various color differences. Finally, the desaturation of color cockpit displays under the very high ambient luminances found at altitude under daytime conditions should warrant a similar laboratory test to determine the pilot's ability to see and distinguish the calligraphics.

COLOR VISION

There are three color vision tests in common use in the Armed Services today. The first is a derivation of the familiar pseudoisochromatic plate test in which the patient is asked to detect and identify a number or figure that is embedded in a randomized matrix of dots. The colors of the dots are selected to lie in or near typical "neutral zones" for various color vision anomalies. Color deficient individuals will be unable to discriminate the hue differences between the dots that make up the number and the dots that compose the "background," and will see no figure or number on the plate. Scoring of the test also attempts to indicate the type of color deficiency. The test is to be given under a specific color temperature lamp, and may yield erroneous results if given under incandescent or fluorescent lighting.

If the patient fails the pseudoisochromatic plate test, he is given an opportunity to take another (more operationally oriented?) test. USAF medical installations may retest color vision with either the FALANT (Farnsworth Lantern) or the USAF CTT (USAF Color Threshold Tester). All three devices are Federal Stock Listed.

The FALANT tests color perception/identification under photopic conditions (normal room lighting). The patient is asked to identify the colors of two vertically positioned spots -- red, white, or green. Several repetitions and all combinations are shown.

The USAF CTT tests color perception/identification under scotopic conditions (blacked-out room). After a period of dark adaptation, the patient is directed to look between two blue guidelamps. On a cue from the examiner, he is to identify the color of the light between the lamps. The stimulus consists of

system's ability to detect an object under any particular condition, we should not measure the pilot's ability to identify letters. On the other hand, legibility of alphanumerics may be predicted by Gaussian analysis, since each alphanumeric may be considered to be composed of a finite number of discrete Gaussian distributions over a relatively circumscribed geometrical area. No overly complex mathematical transforms need be made.

is approached. Negative-contrast Gaussian targets may be produced by exposing a photographic emulsion to light passing through a pinhole (the size of the pinhole and the duration of exposure affecting the size of the target and its contrast). After development, a luminance profile will show a negative Gaussian pattern in the exposed area. Postive-contrast Gaussian targets may be produced by LEDs and pinhole apertures with an appropriate diffuser plate.

Clinical use of Gaussian targets would involve a binary choice test scheme. The patient would indicate whether or not a target was present in a test patch. Test patches would contain various size (spatial frequency or angular subtense) targets, as well as targets of various contrasts. Some test patches would contain no target. Statistical analysis of the responses would set a threshold level, which would define the smallest size (most distant target) or least contrast that could be detectible. Correlation to aircraft target detection under similar conditions of contrast and effective range should be very high, and computerized stimulus presentation and scoring should be relatively easy.

Many of the test methods described in this report can be modified by replacing the existing target with a Gaussian spot target. The ability of the pilot's visual system to detect a moving aircraft may not be highly correlated with his ability to recognize the orientation of a moving Landolt C (these involve completely different aspects of vision), but it should be related to his ability to detect and track a Gaussian target. In this case, identification may not be important, but target detection and track prediction are critical.

The effects of changing environmental conditions (luminance, contrast, etc.) may also be studied with Gaussian targets in a much more realistic manner than with optotypes or gratings. Again, if the task is to determine the visual

GAUSSIAN SPOT DETECTION

Over the years, visual acuity tests have evolved several types of targets for the measurement of the various types of acuity. Most recently, contrast sensitivity measures, using sine waves of various frequencies and contrasts, appear to be in vogue. Although the use of sine waves is exciting in that they lend themselves to mathematical modelling procedures throughout the visual system, and they indeed measure a much wider range of spatial frequencies than does a Snellen acuity test, the target itself does not resemble that which is encountered in the real world. It has been proven that Fourier transforms do not occur at the retinal level, and the ability of the visual system to perform such a transform at any level is only hypothetical.

At the time of first detection, distant objects are seen as a spot. Optical analysis of the retinal image of a distant spot shows it is not a sharp-edged disc, but a Gaussian-like distribution of energy, whose spatial frequency may be defined in two dimensions. There may well be some filtering of this energy distribution as it is processed by the visual system, but the fact remains that the stimulus at the retinal level is indeed a Gaussian-like energy distribution. Gaussian mathematics can be considered more elegant than Fourier mathematics used in sine-wave analysis, and linear systems analysis may also be applied to Gaussian targets. We are aware of the fundamental differences between the visual system's treatment of lines and spots; should it not also be different for sinewaves and Gaussian blobs?

Production of Gaussian targets for clinical use may be less difficult than the production of good sine waves. A Gaussian image is produced by light passing through a small aperture (such as the pupil of the eye, or a pinhole). The distribution of energy is such that it is least at the edges, and quickly (following a Gaussian curve) maximizes as the center of the spot

of 3 orientations: -15, 0, or +15 deg. For each grating, the observer indicates the orientation, or responds that the circle is blank. Contrast sensitivity is the reciprocal of the lowest contrast of the grating whose orientation is correctly indicated in each row. Compared to an electronic display (Optronix), contrast sensitivity using the chart was slightly better at low and slightly worse at high spatial frequencies, and took significantly less time to administer (6 min vs. 12 min).

A chart similar to that described by Ginsburg (1984) is available from Vistech Consultants. An instruction book, test forms, and a light meter are provided with the chart. The near vision tester (18 inches or 45.7 cm) is $420 and the far vision tester (10 feet or 3.1 m) is $570. The spatial frequencies used are 1.5, 3, 6, 12, and 18 c/deg. Potential drawbacks include the fact that only one threshold is obtained for each spatial frequency, creating uncertainty as to just what level (e.g., 50%, 75%,...) of detection or recognition performance is being measured. Variance on this test, as compared to other commonly accepted methods, is high.

Ideal Device

The ideal contrast sensitivity tester for research use would generate accurate waveforms ranging from 0.5 to 32 c/deg in log base 2 steps. Contrast should range from 0.1% to 50% and the display should fill a large proportion of the visual field with an adjustable average luminance of 100 to 300 cd/m^2. The chosen psychophysical method should be quick, require minimal training, and result in a stable threshold. Accordingly, the device should present a preview grating, a contrast ramp from 0.1% to 50%, followed by a series of method-of-ascending-limits trials.

examination device, as well as most phorometers and phoropters. Maddox rods are also available in several hand-held units such as the Curpax monocular.

The Thorington method of measuring phoria uses a row of letters and numerals with the distance between symbols corresponding to one prism diopter. The central position is occupied by an arrow pointing upwards. For the measurement of lateral phoria, a base-up prism is placed before one eye. The resulting perception is of two rows of symbols, one above the other. Heterophoria is noted by the observer saying which letter or numeral the arrow is pointing towards. Vertical columns and a base-in prism allow the measurement of vertical phoria.

Emsley (1962) discusses the use of phoriagraphs, using the presentation of a separate image to each eye. Color filters, polarized filters, or a Wheatstone stereoscope may all be used to achieve this effect. Several commercial versions of phoriagraphs use Badal optics to provide both near and far tests. For example, the Keystone Telebinocular includes tests of lateral and vertical phoria at optical distances of 0 and 2.5 D. For lateral phoria, one eye sees a vertical line of dots and the other a horizontal line scaled in prism diopters. The amount of heterophoria is indicated by the reported intersection of the two lines. Use of a horizontal row of dots and a vertical scale allows the measurement of vertical phoria. The Keystone device has a range of approximately +15 prism diopters.

Similarly, cyclophoria can be assessed by presenting dissociated images of a circular scale and crosshairs to the observer (Wick and Ryan, 1982). The reported tilt of the crosshairs indicates the degree of cyclophoria.

Modifications of the above tests are used in the USAF Visual Function Tester (VFT-1). The VFT-1 presents a two-

dimensional grid, whose cells subtend one prism diopter, to only the right eye. The left eye is momentarily exposed to a small spot of light. The subject reports the apparent position of the light within the grid. This position may be converted to vertical and horizontal phoria components.

Cyclophoria is measured on the VFT-1 by monocularly presenting a series of circles to each eye. The circles encourage vertical and horizontal fusion while allowing rotary or torsional movement. A small portion of the circles presented to the right eye includes one-degree markers. An equivalent portion of the circles seen by the left eye includes a small arrow. The subject reports the number to which the arrow points.

The Duane cover test, described by Borish, is a quick objective test for heterophoria. The subject is asked to binocularly fixate a distant point of light. The examiner alternatively occludes and exposes one eye. Motion of the occluded eye indicates heterophoria. The addition of prisms before the occluded eye aids in obtaining a quantitative measure (the prisms are used to cancel the apparent movement of that eye as it is uncovered). The skill of the examiner determines the sensitivity of the test.

The cover test is one of the few tests that will successfully discriminate between heterophorias (eye misalignment only while dissociated), and heterotropias (eye misalignment both while dissociated and while both eyes are open). All the techniques discussed in this section will yield accurate magnitudes and directions, but differentiating between heterophorias and heterotropias requires measurements to be made both with and without dissociation.

Peli and McCormack (1983) discuss the dynamics of eye movements of both the covered and uncovered eye. Standard

clinical descriptions of the test assume that the fixating eye remains steady. These researchers found that most of their observers made saccadic eye movements in both eyes during both the covering and uncovering phase of the test.

Jamplosky (1968) considers a version of the cover test to be optimum for the measurement of phoria. Basically, the visual environment is under machine control, the cover/uncover sequence is automatic and programmed, and eye movements are recorded and their analysis standardized.

Ideal Device

The ideal test of dissociated phoria should be simple for the observer and scoring should be automatic. Dissociation should be complete and the target display should promote accurate accommodation.

Recent advances in the objective measurement of eye movements (e.g., Crane and Steele, 1978) support the use of a cover test for the measurement of lateral and vertical heterophoria as suggested by Jamplosky (1968). The target should be a single symbol of variable size to correspond to the observer's acuity. Badal optics would allow placement of the target at optical infinity and at a near position of approximately 3 D. Texture surrounding the symbol, such as a checkerboard or square wave grating, would help insure the accuracy of accommodation.

The covering and uncovering of each eye should be quick and automatic. Both eyes should be unobtrusively monitored for horizontal and vertical eye postion and movement. Calibration of the eye movement monitor should be a quick and stable process. A range of +8.6 deg horizontally and vertically would correspond to an acceptable range of 15 prism diopters. An automatic analysis of the eye movement record should be devised

that would make allowance for saccadic movements. Sophisticated programming might be able to identify whether the muscle imbalance is due to a heterotropia or heterophoria.

Accurate (and relatively simple) subjective techniques may involve a method similar to that used in VFT-1, with multiple presentations, in which the "correct" answer varies. Computer recording and analysis of the response can then detect malingering or other anomalous answers, as well as indicate true phorias. Discrimination between phoria and tropia is not performed.

Only relatively esoteric eye movement monitors and techniques would be able to measure rotation of the eye about the line of sight. These include the use of an electromagnetic coil embedded in a contact lens and the tracking of blood vessels on the retina. The measurement of cyclophoria should be adequately accomplished by the dissociated circular scale and crosshairs described by Wick and Ryan and used in the VFT-1.

FIXATION DISPARITY

Fixation disparity refers to the inexactness of binocular fixation during fusion. Similar to the dissociated phorias, it is a measure of oculomotor balance. In contrast to the dissociated phorias, fusion is required. Ogle, Martens, and Dyer (1967) have suggested that fixation disparity may be more useful than other clinical measures of oculomotor balance due to the inclusion of fusion. Abnormal fixation disparities may be associated with complaints of eye fatigue, intermittent diplopia, headaches, and difficulty in performing various visual tasks such as reading and estimating distance (Duwaer, 1983; Sheedy and Saladin, 1983).

Schor (1983) has reported that a correlation exists between the direction of fixation disparity (convergent vs. divergent) and heterophoria (exo vs. eso). Nevertheless, the magnitude of fixation disparity cannot be predicted from the magnitude of heterophoria. At a far test distance of 6 m, exofixation or convergent disparity was shown to increase with esophoria but remained relatively close to zero for most amplitudes of exophoria (Jampolsky, Flom, and Freid, 1957). In contrast, fixation disparity was shown to increase with both esophoria and exophoria at near test distances.

Fixation disparity may be horizontal, vertical, and/or torsional. Horizontal disparity curves have been broken into four classifications by Ogle et al. (1967). These classifications refer to the shape of the disparity curve as a function of a lateral prism vergence stimulus. Compared to horizontal disparity curves, vertical curves are more uniform, taking the form of a linear relationship between vertical fixation disparity and vertical vergence stimuli (Ogle and Prangen, 1953).

Methodology and Instrumentation

The most common method of subjectively measuring fixation disparity is with dissociated nonius lines (e.g., Borish, 1975; Cooper, Feldman, Horn, and Dibble, 1978; Sheedy and Saladin, 1983). The center line separating the nonius lines, the outline of the display, and/or the surrounding texture is viewed binocularly and is fusible. Polarizing filters are used in order to have each eye view a different nonius line. A series of brief exposures of the adjustable line is given until alignment is reported. The physical misalignment of the lines corresponds to the angular fixation disparity.

The Disparometer is an instrument for subjectively measuring fixation disparity at near distances (Sheedy and Saladin, 1983) and is available from Vison Analysis of Columbus, Ohio. Polarized nonius lines are viewed within a circle surrounded by small Snellen charts. One circle is for horizontal and one for vertical disparity. As a control for fusion, observers are instructed to keep the peripheral Snellen charts in clear focus at all times. Adjustments and readouts are provided on the back of the device.

The use of base-in and base-out prisms before both eyes allows a fixation disparity curve to be generated. Typically, the amount of base-out prism is increased until the onset of diplopia or double vision. The fixation disparity curve graphically represents the amount of fixation disparity expressed as a function of the prism power used to drive convergence. The curve type, the slope of the curve near the point of no added prisms, the y-intercept or amount of fixation disparity with no added prisms, and the x-intercept or prism power necessary to reduce fixation disparity to zero have all been considered as measures of fixation disparity (Duwaer, 1983). Subjective measurements of fixation disparity have been shown to be reliable over time (Cooper et al., 1981). These

same researchers found that variability is smallest with no prism and increases with the amount of added prism power.

Duwaer proposed a measure of fixation disparity under "normal" viewing conditions with no interposed prisms. Nonius lines were briefly presented for 20 msec and the threshold for the perception of misalignment was measured. The test was conducted at a distance of 40 cm while observers were looking at typed text. Duwaer reported that the test lasted 20 min. The misalignment threshold and the standard deviation of this threshold were found to be superior to standard measures of fixation disparity (e.g., the alignment threshold, y-intercept, and the slope of the curve) in diagnosing binocular oculomotor deficiencies.

Objective measurements of fixation disparity involve the direct measurement of eye movements. Comparison of the subjective nonius-line method and objective eye movement recordings have shown agreement for horizontal (Hebbard, 1962), torsional (Crone and Everhard-Halm, cited in Duwaer, van den Brink, van Antwerpen, and Keemink, 1982), and vertical (Duwaer et al., 1982) fixation disparities.

Ideal Device

The ideal device would measure fixation disparity at both near and far optical distances (e.g., 2.5 and 0 D). Due to the agreement between subjective and objective methods, a subjective nonius-line method is favored due to its simplicity and cost effectiveness. Resolvable texture, such as that used in the Disparometer, should surround the central display. Both the texture and the central dividing line should be binocular. The "no prism" method advocated by Duwaer appears to be an ideal test due to the normal viewing conditions, and the predictive power of both the threshold of misalignment and the variability of that threshold.

THE NEAR POINT OF CONVERGENCE

The near point has several meanings in the testing of vision. Tests of acuity and phoria, for example, are frequently conducted at both a "far point" and a "near point." The far point is typically at optical infinity, and the "near point" is at a relatively close, fixed distance, frequently 25 cm or 4.00 D. In contrast, the near point of accommodation and/or convergence refers to the closest distance at which a target is still resolvable and/or seen as a single target. This value reflects the maximum amplitude of accommodation (in lens diopters), and/or the distance of the target at the onset of diplopia or suppression.

Since accommodation and convergence are closely related and the stimulation of one results in a response of the other, many "convergence" measures are actually measures of both accommodative convergence and fusional convergence. In addition, the near point of convergence is influenced by the interpupillary distance (IPDs) of the subject. Individuals with wider IPD are required to converge their eyes through a greater angle than individuals with narrow PDs to see targets at similar linear distances from their noses.

The most common method of measuring the near point of convergence (NPC) involves the Prince (or Krimsky) Rule (described under "Near Point of Accommodation") (see also Borish, 1975). With this method, a small pinhead target is gradually brought closer to the subject's eyes until he reports double vision. The examiner observes the subject's eyes during the test, and notes if one eye or the other "loses track" and suddenly diverges (or stops converging). The endpoint of the test is either the subjective report of diplopia or the objective report of loss of convergence tracking. Since accommodative convergence is stimulated by the use of this

method, the result is not a measure of pure fusional convergence amplitude.

Roper-Hall (1983) discusses the use of prisms to measure the amplitude of convergence. Base-out prisms are added before each eye until the subject reports diplopia or movement of the target to one side or the other (indication of suppression). Similar to the Badal optometer, prisms allow constant target size to be maintained, and are not influenced by the various interpupillary distances likely to be encountered. Accommodative convergence is not stimulated, resulting in a truer measure of fusional convergence.

With both the near-point rule and the pinhead devices, the visual angle of the target increases as it is brought closer to the observer. This probably has less effect on the measurement of NPC than it does on the measurement of near point of accommodation (NPA). In addition, two mechanisms are simultaneously occurring. Insufficient accommodation will cause refractive error and blurring of the target, and insufficient convergence will result in diplopia or doubling of the target. Objective eye movement monitors and optometers usually lack the range necessary for adequately measuring convergence and accommodation at the near point.

Most present methods measure only along the centerline of the binocular lines of sight. There is no commonly accepted measure of convergence when the eyes are fixated to one side or the other. Since the medial rectus is the primary extraocular muscle controlling convergence, this may appear to be satisfactory; but the influence of different antagonistic muscles for various points of view are unknown. Other measures of convergence may be obtained with devices described by Ciuffreda and Kenyon (1983) and Owens and Leibowitz (1980, 1983) (see the section on "Near Point of Accommodation").

Ideal Device

The ideal device should be capable of objectively measuring the near point as indicated by diplopia or suppression. It should be free of, or compensate for, the effects of interpupillary distance. Separate measures of accommodative convergence and fusional convergence should be available. Although it is commonly accepted practice to record this value in cm or inches, prism diopters may be more appropriate since rotating prism methods appear to be quite accurate. On occasion, "meter angles" may be used to describe the effects of interpupillary distance and convergence effort.

Test device ranges are commonly 1 m to 1 cm (measured from the bridge of the nose). The target should be small, of high contrast, and maintain a constant visual angle at all distances. Variable prism devices appear to provide adequate stimuli for measures of fusional convergence, but responses must remain subjective in the absence of effective eye tracking devices.

TRACKING OF MOTION IN DEPTH AND IN THE FRONTAL PLANE

News programs on television frequently try to depict economic inflation by showing a shrinking dollar bill. What the viewer actually perceives is a bill of invariant size that rushes away in the distance. Whenever a rigid object undergoes a change in visual angle, the observer perceives motion in depth. A decrease in visual angle corresponds to an object moving away from the observer, and an increase in visual angle corresponds to an object approaching with the rate of increase proportional to the imminence of collision (Gibson, 1979).

The perceptual experience of motion in depth appears to be "hard-wired" in the visual system and not dependent on learned or computational processes. Gibson has described this in terms of direct perception, while Regan and Beverly (e.g., Kruk, Regan, Beverly, and Longridge, 1981, 1983; Regan and Beverly, 1978, 1980) have discussed channels in the visual system tuned to depth and direction.

Kruk et al. attempted to relate several psychophysical tests to flight simulator performance and the flying grades of pilots. Threshold measures failed to distinguish pilots from nonpilots. In contrast, a suprathreshold tracking task involving antiphase motion (motion in depth) and inphase motion (motion in the frontal plane) successfully made this distinction. The tracking task also corresponded most closely to simulator performance.

Methodology and Instrumentation

Regan and Beverly (1980a) describe the measurement of tracking of a 0.5 x 0.5 deg solid square target displayed on a CRT. For the antiphase tracking task, the square expanded at a rate of 13 min per sec per edge. After a pseudo-random interval, the square contracted at the same rate. The

observer's task was to keep the square at a constant size using a control knob. For inphase tracking, opposing sides of the square moved in synchrony. This resulted in the square translating along a diagonal path in the frontal plane. The observer's task was to track the square in order to null its motion. Tracking error was expressed in arbitrary RMS units.

Ideal Device

Pending further research, no improvements in the methodology and instrumentation of Kruk et al., and Regan and Beverly are suggested.

MEASURES OF ACCOMMODATION

Accommodation is the process whereby the focal length of the eyes adjusts to maintain a clear image of the object of regard -- whether that object be located at some far distance, or relatively close. The sufficient stimulus for accommodation may be retinal blur.

Accommodation is increased (for clear vision of near objects) by relaxation of the radial fibers of the ciliary body, thereby allowing the eye lens to assume a more spherical shape. The maximal range of accommodation decreases from about 30 diopters in infancy to 0 diopters in old age. The minimal distance seen clearly with the maximum amount of accommodation is often called the near point of accommodation.

In the absence of refractive error, the amount of accommodation necessary to clearly image a target may be calculated by taking the reciprocal of the target distance in meters. Beyond 6 meters is usually considered optical infinity for the eye. If refractive error is present, the required accommodation to clearly see a target at any specific distance is calculated by considering both the distance and refractive error.

The pupils of our eyes act as aperture stops and, when small, can increase the depth of field, or range in which we can see relatively clearly. On average, our depth of field is about 0.50 D.

When the accommodative mechanism has attained its "resting state," or when the eyes are in total darkness, the conjugate point of focus does not appear to be at optical infinity, but at some intermediate point between infinity and the near point of accommodation. Measures of dark focus attempt to define this intermediate point. Dark focus or resting state measures may be

rtinent to pilot vision, since the outside scene often does t present enough detail to "pull" accommodation to infinity. e resultant "night myopia" will make detection of small, stant targets more difficult.

Measures of maximum accommodation may also bear some elationship to aircrew visual performance. Standards for efractive error allow hyperopes to be selected as pilots. sually, hyperopes do not wear glasses since their vision is ubjectively clear without them. As hyperopes age and resbyopia increases, so does the accommodative demand to see learly at near point. Presbyopic pilots have difficulty eading maps and written material under red light (because red ight requires more accommodation than other wavelengths), or nder dim illumination (because of the larger pupil and reduced epth of field). Nearby visual displays and instruments will be lurred, but distant vision usually remains fairly clear. ccommodative tests not only chart the progression of resbyopia, but demonstrate to the pilot that he needs near oint correction for optimal near vision.

Since near-point tasks frequently involve reading written r displayed material, clinical accommodative tests should mploy similar stimuli to maintain valid comparisons. For esearch purposes, finer measures of accommodative ability can e made with laser or vernier optometers, but the patient (and ometimes the examiner) often cannot relate the test to the equirements of the visual task.

A laser or vernier optometer can be built as a single-lens ›dal system or a dual-lens Badal/focus-stimulator system. The tter requires the second lens to shift axially in order to ange the optical distance of a stationary target (either the ser speckle or the vernier bars). Advantages of a dual-lens stem are the ease of translating a lens rather than a rotating linder or vernier bars and a lamp, the ability to control pil size, and the availability of an off-the-shelf focus imulator from Stanford Research Institute (Crane and Clark, 78) that uses high-quality camera lenses and can be corporated into either a laser or vernier optometer.

Simonelli (1980b) compared laser and vernier optometers and ›und good agreement between the two devices in measuring the ırk focus. For 20 observers, a correlation of +.81 was ›ported. The depth of focus or *neutral zone* was 0.39 D for the ıser, and 0.35 D for the vernier instrument, a difference that as not statistically significant. A post-experiment uestionnaire found the vernier optometer to be more ıcceptable" to observers in terms of the ease of making a iscrimination, confidence in these discriminations, and the ıse of maintaining head position.

Randle (1983) has designed a dual-lens optometer that is ısed on the Scheiner principle and uses pinholes rather than ›larizing filters. Any target, such as a bar, observed through ıe two pinholes will appear single only if the eye's focus ›rresponds to the distance of the target. The use of Badal ›tics allows the pinholes to be placed at the effective pupil lane of the eye. The optometer measures approximately 30 x 14 80 cm.

A haploscope (Cuiffreda and Kenyon, 1983) requires the ›server to report when a small disk is in focus while a ›imulus display is being viewed. The optical distance of the

onresponsive to it (Hennessy and Leibowitz, 1970), and the use of aser light, which is a potential hazard to vision.

Laser optometers are usually built as prototypes for aboratory use. The availability of an off-the-shelf unit is ot known. The size and weight is primarily dependent on the aser, shutter, and motor/cylinder. The use of a short focal ength lens will minimize both factors, but may degrade ensitivity or accuracy.

The polarized vernier optometer is based on the Sheiner rinciple whereby the retinal image of a point of light passed hrough different parts of the lens will be single only if the efraction of the eye's optics corresponds to the distance of the oint source. The vernier optometer, by the use of polarizing ilters, passes half of a bar through the top half of the lens nd the other half through the bottom half of the lens. If the bserver indicates that the bars are aligned, then the distance f the target corresponds to the magnitude of accommodation. As ith the laser optometer, the use of a Badal viewing system reatly extends the range of measurement (Simonelli, 1980a, 1983). In addition, a large pupil will minimize the depth of ocus or neutral zone, the dioptric range in which the vernier ars are reported to be aligned. Unfortunately, large pupils lso emphasize the spherical and chromatic aberrations of the ye, resulting in different dioptric values from those found ith smaller pupils.

Advantages of the vernier optometer include the low cost, he use of low-level incandescent light, the potential ompactness, and the easily understood task. Disadvantages nclude the critical vertical alignment of the observer such hat the polarizing filters split the pupil, and the fact that a udgment is required from the observer. The size and weight is rimarily dependent on the lamp, focal length of the lens, and hether a shutter is used or the lamp electronically pulsed.

images by reflection of the ocular fundus. Although Lovasik does not specify the accuracy, examination of several time series indicates that it probably approaches 0.1 D. It is susceptible, however, to translation movements of the eye. It also requires that eye movements, head movements, and pupil changes be minimal -- indicating the necessity of a bite bar. Major advantages of this instrument include its compact size, simple design, and low cost (less than $500).

Subjective Instruments

The laser optometer operates on the principle that coherent laser light reflected off of a rotating cylinder will appear as speckle "flow" if focus does not correspond to a plane near the cylinder's surface (Charman, 1979a, 1979b; Hennessy and Leibowitz, 1970, 1972; Ingelstam and Ragnarsson, 1972; Knoll, 1966; Leibowitz and Hennessy, 1975). Hennessy and Leibowitz combined the laser optometer with the principle of the Badal optometer in order to greatly extend its range. Bahuguna, Malacara, and Singh (1984) describe how white light can be substituted for laser light.

Clinical refraction can be accomplished by putting the rotating cylinder at optical infinity and placing trial lenses before the eye until the speckle flow is stopped. For psychophysical experimentation, the cylinder's distance is varied until no speckle flow is reported. Brief exposures and a bracketing procedure are typically used. A large pupil will minimize the depth of focus or neutral zone, the dioptric range in which no speckle flow is reported.

Advantages of the laser optometer include the low cost, noncritical observer alignment, and the modest amount of observer and examiner training required. Disadvantages include the fact that the measurement of accommodation is based on the observer's judgment, and a small proportion of observers are either not able to perceive the speckle flow or are

laser optometer, the average mean difference between the three to four month measurement periods was 0.21 D. Examination of the individual time series does reveal that considerable fluctuations occur from day to day and week to week. One diopter shifts over these periods were common. One-time measurement sessions may also produce biased results. Moffitt (1983) has noted that an initial measurement session with an inexperienced observer may result in an inflated dioptric value of the dark focus.

Methodology and Instrumentation

Objective instruments:

Objective optometers measure accommodation by monitoring either infrared retinal reflections (e.g., Crane and Steele, 1978; Lovasik, 1983) or the third Purkinje Image (e.g., Allen, 1949; Wulfeck, 1952). These optometers are relatively unobtrusive instruments that have a high degree of resolution and are capable of measuring the dynamics of accommodation. Disadvantages typically include the expense, the required precise observer alignment that necessitates the use of a bite bar, the need for a dilated pupil, the disruption by eye movements, and the complicated electro-optics and mechanics.

While most instruments are prototypes, Stanford Research Institute manufactures an "off-the-shelf" device that may be integrated into an eye-tracking system or used as a stand-alone unit. The optometer optics weigh approximately 2.7 kg and the electronics weigh 9 kg and measure 20.3 x 50.8 x 48.3 cm. The price for the SRI optometer is approximately $28,500.

Lovasik (1983) describes an infrared optometer that is similar to many laboratory prototypes, but is somewhat smaller and simpler in design. Basically, the optometer detects the accommodation-dependent separation of two infrared extraocular

also exhibits a considerable range of values at any given age. For college age observers, Simonelli reported a range extending from beyond optical infinity to +14 D (0.07 m). Simonelli also reported a signficant difference between the dark foci of students and Air Force recruits (2.70 and 1.20 D, or 0.37 and 0.83 m). When only those observers with an uncorrected far acuity of 20/25 or better were considered, the dark foci for the students and recruits (0.85 and 0.59 D, or 1.2 and 1.7 m) were not significantly different, but were more distant than the more general populations.

The dark focus can be affected by nonvisual factors such as stress, workload, and visual imagery. Although the actual measurement of the dark focus is relatively quick and simple, care must be taken that the observer is in a relaxed state. The usual precaution is to let the observer relax in the dark for several minutes prior to data collection.

The position of the dark focus, and resultant visual performance, can be influenced by optical aids. The use of optical correction has been shown to improve acquisition performance for small, distant targets. Post, Owens, Owens, and Leibowitz (1979) corrected the dark foci of observers to optical infinity with an auxiliary lens. A small target, located at optical infinity, was presented in an otherwise empty field. The performance of all observers improved with optical correction, with the more myopic observers showing the greater improvement. A similar experiment by Luria (1980) found the correction of empty field myopia to improve contrast sensitivity. The most benefit was found for small targets and by the more myopic obervers. Murch (1982) has also advocated the use of optical correction for CRT operators in order to enhance visibility.

Owens and Higgins (1983) reported that the dark focus exhibits considerable stability over a one-year period. Using a

THE DARK FOCUS

The dark focus is the intermediate resting state of visual accommodation that is found when an observer is placed in the dark or in a ganzfeld or empty field. Convincing evidence supports a dual innervation theory of accommodation, whereby the resting or relaxed state does not correspond to optical infinity, but to some intermediate point representing the natural balance point created by the dual innervation of the sympathetic and parasympathetic branches of the autonomic nervous system (e.g., Benel, 1979; Cogan, 1937; Simonelli, 1980b; Toates, 1970, 1972).

Several researchers (e.g., Benel and Benel, 1979, 1981; Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1983; Owens and Leibowitz, 1975) have found the resting point of accommodation to be the major determinant of focus in the absence of signficant optical texture. This phenomenon has been termed empty field or night myopia and would be expected in many air-to-air and night target acquisition scenarios. Owens and Leibowitz, for example, reported that a luminous fixation point presented in the dark at distances of 2.00 and 0.25 D (0.5 and 4.0 m) was not an adequate stimulus for accommodation. Rather, the accommodative status was primarily determined by the individual's dark focus.

The dark focus has also been found to be a major determinant of the accuracy of accommodation to CRT screens. Depending on the type of display being viewed, Murch (1982) reported that accommodation fell somewhere between the dark focus and the distance of the display. Compared to hard copy, all of the CRTs caused a regression towards the dark focus.

Individual variables have been found to affect the dark focus. A common finding (e.g., Simonelli, 1980b, 1983) is the outward migration of the dark focus with age. The dark focus

outwards in optical distance produced false breakpoints in the vernier, probably due to microfluctuations of accommodation. Inexperienced observers tended to interpret these breakpoints as the far point. Moving the display inwards, starting well beyond optical infinity was found to produce a more stable measure of the far point.

The vernier bars that occupied the center of Simonelli's display may not constitute an optimum stimulus to accommodation, although the inclusion of texture in the periphery is desirable. Considerable evidence suggests that the accommodative system is responsive to both central and peripheral texture. For a central display, Charman and Tucker (1977, 1978) found that a 10 c/deg sinusoidal grating, or small targets such as Snellen letters, elicited the most accurate accommodation.

Ideal Device

The ideal research device for measuring the far point of visual accommodation would be objective, unobtrusive, provide an optimum stimulus to accommodation, and have a range of +6.00 to -4.00 D with a sensitivity of 0.1 D. Infrared optometers approach this ideal, although subjective optometers or judgments of blur may be clinically useful.

THE FAR POINT OF ACCOMMODATION

The far point has several meanings in the testing of vision. Tests of acuity, phoria, and stereopsis are frequently conducted at both a "near point" and a "far point." In this context, the far point refers to an arbitrary far distance, typically 20 feet or optical infinity. In contrast, the far point of accommodation (Punctum Remotum, or PR) will refer to the greatest distance to which an observer can accommodate.

For myopes, the far point of accommodation (that point in space which is in conjugation with the retina when parasympathetic innervation to accommodation is totally absent) is closer than optical infinity. For emmetropes, the PR is at optical infinity. For uncorrected hyperopes, that distance is (mathematically) beyond infinity, and is represented as a virtual point behind the subject's head. As with other measures of accommodation, the farpoint is not a point in space, but a range, which is affected by the depth of focus of the eye.

Simonelli (1980b) found that the far point of accommodation migrates outwards with age, with a considerable range found at any given age. There was also significant difference between the far points of students and Air Force recruits for both the overall sample (0.52 m vs. 2.12 m, or 1.92 D vs. 0.47 D, respectively) and for those observers with far acuity of 20/25 or better (6.66 m vs. beyond optical infinity, or +0.15 D vs. -0.12 D.) In the overall sample, a considerable number of observers were able to accommodate beyond optical infinity.

Methodology and Instrumentation

Simonelli (1980a, 1980b) used a vernier optometer to measure the far point. The observer attempted to focus and align the vernier bars, which were surrounded by a checkerboard texture. He found that moving the vernier/checkerboard display

The accommodation system is responsive to small oscillations (less than about one D) at frequencies up to four cps. In contrast, the vergence system is relatively insensitive to movements above approximately one cps. These estimates are dependent on the stimulus magnitude and the predictability of the signal.

Ideal Device

The ideal device for measuring static NPA should be capable of objectively and separately measuring the monocular and binocular near points. Both measures should be expressed in terms of optical distance, accurate to at least 0.25 D, with a range of 0 to +20 D. The target should be small, of high contrast, and maintain a constant visual angle at all distances. Lens or Badal systems appear to meet these constraints.

The ideal device for objectively measuring dynamic accommodation would dynamically stimulate and measure refractive accommodation, as well as vergence-associated accommodation. Range magnitudes up to several diopters should be provided. Sine and square waves ranging from 0.2 to 3.2 cps in log base 2 units should be used. Subjective measurement devices would depend on the timeliness of responses from the subject, but would be less complex in nature.

Methodology and Instrumentation

An infrared optometer is required for the objective measurement of dynamic accommodation. Similarly, a motor-driven focus stimulator is required for the generation of the target motion in dioptric depth. Infrared devices for measuring dynamic accommodation and vergence are objective and relatively unobtrusive. Specifically, they do not require the observer to make a judgment. Cooper, Ciuffreda, and Kruger (1982) and Ciuffreda and Kenyon (1983) describe a device that corresponds to the response AC/A ratio and measures accommodation in the viewing eye and accommodative vergence in the occluded eye.

The Stanford Research Institute three-dimensional Eyetracker/Optometer (Crane and Steele, 1978) is a sophisticated infrared device that can simultaneously track accommodation and eye movements in the same eye. A pair of Trackers can be used to assess binocular performance. Furthermore, an SRI focus stimulator and visual deflector (Crane and Clark, 1978) is capable of driving visual stimuli in three dimensions. Again, a pair can be used to provide binocular stimulation. These instruments could be adapted to measure accommodation and vergence during natural viewing.

Stark (1968) has dealt with the problem of servoanalysis of dynamic accommodation using a nonlinear frequency-response approach. Basically, a target is oscillated in dioptric depth and the resulting tracking performance of the observer is measured. A transfer function analysis provides gain and phase angle information. Gain is the ratio of output to input magnitude and phase angle describes the relationship of output to input in terms of lead or lag. With increased frequency and/or amplitude of a sinusoidal signal, the gain decreases and the phase angle increases (Ciuffreda and Kenyon, 1983).

varied, is in clear focus. Placement of the markers above and below the stigma indicates the magnitude of vergence.

An apparatus for measuring steady-state accommodation and vergence has also been described by Owens and Leibowitz (1980, 1983). A laser optometer was integrated with a nonius alignment technique such that vernier bars were composed of laser-speckle. Observers judged when the speckle flow was stabilized (the measure of accommodation) and the vernier bars aligned (the measure of vergence). In contrast to the device described by Ciuffreda and Kenyon, viewing is binocular.

Dynamic Accommodative Measurements

The human lens is in continual motion. Microfluctuations describe the small (about 1/10 D) oscillations of accommodation that peak in spectral power at about 1/4 cps and increase in magnitude with close accommodation. These microfluctuations may aid in shifting the "steady-state" component of accommodation, allowing the observer to refocus on a new display or target. Problems in shifting focus have been associated with problems in such tasks as viewing CRTs and using HUDs. In addition, myopes exhibit a "stickiness" when attempting to track a target in dioptric depth.

As shown above, most experimental and clinical measures of accommodation and vergence are static in nature. This is partly due to the expense and difficulty of taking dynamic measurements, especially simultaneously measuring both responses. In addition, the lack of data bases for these dynamic processes make interpretation difficult. Nevertheless, relying on static measures out of convenience may produce misleading results.

Since lens power (or accommodation) is related to the reciprocal of the distance from the eye, relatively small changes in position near the eyes will result in a larger dioptric stimulus change than similar positional changes occurring farther from the eyes. In other words, push-up rules are less accurate as the near point is approached.

Another failing of the push-up method is related to the apparent size of the target. The angular subtent of the target increases as it approaches the eyes. In some cases, this change of angular subtent can add an error factor to the readings. To help eliminate this source of error, another method involves holding the target at a specified fixed distance from the eyes and adding minus lenses until the target 1) becomes slightly blurred, or 2) blurs to illegibility, or 3) is seen as two (diplopic) images. This method is more accurate in that lenses can be varied in steps of as little as 0.125 or 0.25 D. Unfortunately, the addition of minus lenses in front of the eye plane, and the resultant increase in plus power of the eye lens, contributes to a minification of the target size, perhaps adding another error source. The increased time of administration of the test might also add to accommodative muscle fatigue.

Somers and Ford (1983) compared Donder's pushup method with a Badal optometer technique -- the use of a lens to maintain constant visual angle and luminance. The pushup method resulted in 0.6 D more amplitude than the Badal optometer method.

Ciuffreda and Kenyon (1983) describe a Haploscope-optometer, a device that provides static or steady-state measures of the response accommodation and convergence ratio. The target's optical distance is varied along the line of sight of one eye by means of a Badal optometer. The change in direction of the occluded eye is assessed by means of a mirror and markers. Accommodation is measured by having the observer respond when a stigma, the distance of which is independently

Simonelli (1980b, 1983) measured 301 eyeballs and reported a recession of the near point with age. At any given age a wide range of near points was found, especially among college-age observers whose near points ranged from 0.40 to 0.04 m, or 2.5 to 22 D. In this same study there was an insignificant difference between the near points of students and Air Force recruits. However, when only those observers with a far acuity of 20/25 or better were considered, the recruits had significantly closer near points.

Simonelli briefly discusses the monocular near point, which requires no binocular fusion. He suggests that less discomfort is associated with monocular compared to binocular measures. Furthermore, the monocular near point would be expected to yield a value several diopters less than the binocular near point (because of the relative absence of convergence accommodation). The monocular near point is frequently referred to as the monocular amplitude of accommodation (Borish, 1975). An abnormally low amplitude may indicate a retinal or post-retinal pathology, or an inflexibility of accommodation (Somers and Ford, 1983).

Methodology and Instrumentation

Donder's pushup method uses a near point rule that displays small, high contrast targets that are moved towards the observer's nose until the targets are no longer resolvable. This distance defines the near point. The recommended method included in USAF eye test manuals is based on Donder's method, but, interestingly, requires that the target be moved from a position very close to the eyes to the point of first resolution. One device which uses this method is the Prince (or Krimsky) Rule.

One problem with push-up rules involves the effective lens power change per unit distance at any particular distance.

THE NEAR POINT OF ACCOMMODATION; DYNAMIC ACCOMMODATION

Static Accommodative Measurements

The near point of accommodation refers to the closest distance at which a target of specified size is still resolvable. This value reflects the maximum amplitude of accommodation (in lens diopters). The range of accommodation is the difference between the farpoint of the eye (the farthest dioptric distance at which a target can be seen clearly) and the near point.

To simplify matters, and avoid erroneous results, accommodation testing is done through the patient's best (distant) corrective lenses. This precaution theoretically places the farpoint at optical infinity and equates the near point of accommodation to the range of accommodation. If lenses were not used, and two subjects (one hyperopic and the other myopic) of equal range of accommodation were measured, the hyperope's near point would be artifically farther from the eye, and the myope's near point would be artificially nearer -- both by an amount equivalent to the subject's distant lens correction.

The accommodative near point may be measured either binocularly or monocularly. The binocular near point is largely a function of the amount of accommodation, convergence and associated discomfort that an observer is willing to endure (Simonelli, 1980a). Since accommodation and convergence are highly interactive, binocular accommodation may be stimulated not only by the divergent light from a near target, but by the convergence of the eyes required to maintain single binocular vision. The former type of accommodation may be termed "refractive accommodation," while the latter may be called "convergence accommodation."

disk is independent of the display. The distance at which the disk is reported to be in focus is assummed to be the distance of accommodation. An obvious disadvantage of this method is that it requires judgments of blur and clarity in which substantial individual differences would be expected.

Finally, Borish (1975) describes a number of clinical techniques for determining the focal power of the lens. Most of these techniques involve visible light, are relatively obtrusive, and require a highly skilled examiner, making them inappropriate for inclusion in an automated vision tester.

Ideal Device

An ideal research instrument for measuring the dark focus would be unobtrusive, not require critical eye positioning, have an accuracy and resolution of 0.1 D, have a range extending from -2 to +6 D (past optical infinity to 0.17 m), tolerate a range of pupil sizes without sacrificing resolution, allow eye movements, be able to be easily calibrated using an artificial eye, require minimal examiner and observer training, and be relatively simple in design in order to facilitate maintenance and repair. As yet, no instruments are available that have all these features.

NEUROLOGICAL STATUS

There are several visual tests that do not easily fit into the section headings chosen for this document. Neuro-ophthalmologic tests such as pupil size and reaction, dark adaptation, visual fields, Haidenger's Brushes, etc. were not included. However, two other test subjects have been included: critical fusion frequency and a discussion of fusion, diplopia and suppression.

CFF may be used as a determinant of neural activity under extreme environmental or fatigue conditions, and the ability to maintain single simultaneous binocular vision may be important to optimal visual performance in the cockpit.

CRITICAL FLICKER FUSION

The temporal frequency at which a modulating light transitions from perceived flicker to an apparent steady light (fusion) is termed the critical flicker fusion, critical flicker frequency, critical fusion frequency, or CFF. CFF is considered useful for specifying permissible frequencies of lights, depending on whether the designer desires the display to appear steady-state or to flicker as a warning signal. The transition from flicker to fusion appears to occur as some neurological frequency limit is passed. There is also good evidence that the CFF threshold is influenced by factors such as drugs, fatigue and hypoxia, and may show the effect of these factors on the neurophysiological system as a whole.

Although most of the flicker found in the real world approximates square or rectangular waves, the current research trend is to use sinusoidal waveforms in order to employ the principles of Fourier analysis (e.g., Kaufman, 1974; Kelly,

1972). Clinical or screening instruments may well use square wave stimuli.

Brown (1965), Kelly (1972), and Sekuler, Tynan, and Kennedy (1981) have all reviewed the CFF literature and general findings in this paper have been obtained from these sources. In addition, Landis (cited in Ginsburg, 1970) has compiled an annotated bibliography of CFF publications from 1740 to 1952, and Ginsburg has continued this bibliography through 1968.

A repeated finding is that CFF increases with the luminance of the display. That is, the sensitivity of the visual system to higher temporal frequencies of flicker increases as the intensity of the stimulus increases. Over an intermediate range of stimulus luminances, CFF and log luminance are approximately linear. The relationship between CFF and the logarithm of the area of the display is also approximately linear.

The effect of retinal eccentricity on CFF is a complex function that is luminance and area dependent. For example, at high luminances CFF declines with retinal eccentricity. In contrast, at very low luminances CFF is higher in the periphery than at the fovea. CFF is approximately constant across the retina for intermediate luminances. These findings tend to hold for small to intermediate size displays. For large displays such as a CRT, the periphery is more sensitive to flicker than the fovea, even at intermediate luminances.

The spatial composition of the flickering display has also been shown to affect CFF. At moderate flicker rates, the presence of sharp contours or intermediate spatial frequencies increases sensitivity. An analogous effect at high temporal frequencies has not been found.

Observers have reported that the CFF task is easiest to perform if the luminance of the field surrounding the flickering

display is matched in brightness to the display. Eliminating the surround frequently results in reports of glare, discomfort, and even headaches. Although the size of the surround does not actually affect CFF, the luminance of the surround does have an effect.

The highest CFF for a foveal display is achieved with a surround that matches the stimulus in brightness. For a peripheral stimulus, the highest CFF corresponds to a surround that is less intense than the stimulus. The effect of the illumination ratio between the surround and flickering stimulus has been found to be greatest for one minute of arc stimuli and to have essentially no effect for either smaller or significantly larger stimuli.

Other variables affecting CFF include the level of adaptation, the wavelength of the stimulus, the temporal frequency of the surrounding field, the shape of the stimulus, the number of flashes, and observer characteristics such as age. In general, these factors tend to form complex interactions with spatial, temporal, and intensity characteristics of the stimlus.

DeLange (1958a, 1958b) and Kelly (1972) have advocated the use of the sinusoidal waveform to study the response to flicker. This approach requires the temporal frequency of the flickering display to be an independent variable and the modulation or contrast at which flicker is detected to the be the dependent variable. Analogous to spatial vision, the psychophysically measured temporal modulation function peaks at an intermediate frequency. This peak shifts to a higher frequency with increased display luminance and area.

Methodology and Instrumentation

The most common device used to produce a flickering display is a light chopper consisting of a slotted, rotating disk. The

size of the slot and the speed of rotation determine the temporal frequency of the flicker. This method is suitable for generating either square or rectangular waveforms. The device would essentially consist of a light source, disk, motor, and speed controls.

Gas discharge tubes have also been used to generate square waves. The disadvantage is that a shift in temporal frequency is accompanied by a shift in color.

The most common technique for producing sinusoidal waveforms is to rotate a polarized filter between two out-of-phase fixed polarizers. An analog motor with a speed control would be suitable for spinning the central filter.

Computer software has been used in conjunction with a graphics interface to turn on and off appropriate portions of a display. With a conventional CRT, the highest temporal frequency of the generated square waves is limited by the cycle time of the display. One other approach is to drive the Z-axis amplifier of a CRT with a function generator. Alternatively, the function generator could be implemented in software. Both approaches would allow the production of a number of waveforms. The Nicolet Optronix Series 200 Vision Tester includes a CFF test on a CRT. The unstructured display field may be flickered at rates up to 30 cps.

Several solid state circuits have been designed that drive a light-emitting diode (LED). The advantages of these circuits include their compactness and absence of noise. The fact that LEDs are spectrally narrowband should be considered.

Frey (1979) describes a solid state device that generates square waves, using an LED, at rates ranging from 10 to 200 cps. This device is self-contained, with the flash rate controlled by a potentiometer. A more flexible device is offered by Beaty

and Corwin (1983). This device allows the luminance of the LED to be linear with respect to an externally supplied voltage. A digital to analog converter could easily be interfaced to this device in order to provide any desired waveform and frequency. The AFAMRL VFT-1 uses square shaped, filtered, and diffused LEDs to produce CFF stimuli across a wide range of frequencies.

Ideal Device

The ideal research instrument would have flicker rates that were continuously variable to at least 60 c/sec, a variable stimulus size, a large surrounding field that matched the display in brightness, allowance for central or peripheral viewing, and the capablility of generating several types of waveforms. This device should also be able to modulate the intensity of the flickering display in order to obtain temporal modulation functions. For clinical or screening devices, holding many of the variables constant (standardizing on a set of variables), and allowing control only of the frequency, would be optimal.

FUSION, DIPLOPIA, AND SUPPRESSION

Some authorities indicate there are three grades of fusion: 1) Simultaneous perception (sometimes called "fusion readiness," 2) Fusion (a single visual image), and 3) Stereopsis. This section will address second-degree fusion, or the binocular coordination of the eyes' muscular and perceptive systems that results in a single visual image.

The presence of fusion should be ascertained prior to the administration of tests of phoria, accommodative-convergence, and stereopsis in order to avoid ambiguous results from these tests. It is important to realize that the presence of second-degree fusion implies neither the presence of orthophoria, nor that stereopsis is intact.

Panum's area is the region of tolerance for retinal disparity and corresponds to single vision. Outside of Panum's area, diplopia or double vision occurs. A wide range of values for Panum's area or the diplopia threshold have been reported. This variance has been attributed to observer, methodological, and display factors (Duwaer and van den Brink, 1981; Warren, Genco, and Connon, 1984).

Given that corresponding areas of each retina are stimulated with similar displays, certain individuals may suppress one of the images. Warren et al. have suggested that the incidence of suppression has been underestimated.

Under optimal conditions, the complete absence of fusion is relatively rare. Henderson and Burg (1974) have suggested that a marginal visual environment, such as the lack of textured surfaces or a low-contrast target, may be required to reveal fusion deficiencies.

Methodology and Instrumentation

There are two basic approaches to the assessment of binocular fusion, diplopia, and suppression. The first is to present a single target to both eyes, or to stimulate corresponding retinal points in each eye, and to obtain a report from the observer of the resulting image. The second is to measure the threshold for singleness or doubleness of vision in terms of retinal disparity.

Borish (1975) describes a quick test for fusion that involves corresponding retinal points. Observers view a white dot target against a dark background, with a red filter in front of one eye and a base-up or base-down prism in front of the other. The prism serves to create diplopia or the appearance of two dots, one red and one white. The prism is quickly removed and the observer reports (1) a single pink dot -- indicating fusion, (2) two dots which slowly drift together -- poor fusion, (3) no change -- no fusion, or (4) a single red or white dot -- suppression of one monocular image. The report of a single white dot should be checked to insure that it is not actually pinkish. This can be accomplished by removing the red filter. If the dot now appears greenish, the red filter eye was operational and fusion took place. If there is no change, the red-filter eye was suppressed.

The Keystone Telebinocular vision tester includes a test of binocular coordination at the far point. The observer is presented with two dissociated displays, each consisting of two vertically aligned "balls." The upper ball in the left display and the lower ball in the right display stimulate corresponding retinal points -- creating zero disparity. The other two balls have sufficient disparity to achieve diplopia and appear as separate images. Immediately upon exposure, the observer reports (1) three vertically aligned balls -- indicating that the eyes are habitually postured for single binocular vision or

fusion readiness, (2) three balls in oblique alignment -- indicating heterophoria and the need for effort to achieve fusion, (3) four balls, quickly merging into three balls -- indicating slightly sluggish fusion readiness, (4) four balls slowly merging into three -- marginal fusion, (5) four balls -- marked interference in the accommodative-convergence relationship or weak fusional convergence, or (6) two balls -- indicating suppression, look for amblyopia and strabismus.

Duwaer and van den Brink (1981) and Warren et al. (1984) both question the validity and usefulness of previous reports of diplopia thresholds or Panum's area. Duwaer and van den Brink presented observers with a dichoptic display of horizontal line segments, each measuring 30 x 1 min of arc. After each presentation, observers reported whether they perceived a single line, a double line, or were uncertain. The retinal disparity was varied until thresholds were reached. This three-alternative choice allowed the estimation of both singleness (fusion) and doubleness (diplopia) thresholds.

Warren et al. measured the diplopia threshold in a head-up display (HUD) simulation using a relatively large sample (N = 32). Observers viewed an outside scene which included a white pole at 1.4 km, and indicated whether a briefly presented, superimposed green line appeared single or double. The report of a single green line offset to one side of the distant pole indicated suppression of one of the monocular images. Two exposure durations (100 msec and 3 sec) and both disparity directions (crossed and uncrossed) were tested. The diplopia threshold was highest for positive disparity and the 100 msec exposure. A surprising finding was the relatively large proportion of suppression reports. For example, suppression occurred on 31% of the trials for the positive disparity and 100 msec exposure condition. The high occurrence of suppression reports may have been due to the distant viewing and the complex

real-world background, factors that are usually absent in such experiments.

Ideal Device

The ideal device for the measurement of binocular fusion should allow for multiple levels of response, ranging from fusion readiness to stereopsis. Controls should be included to indicate which eye experiences suppression, if it occurs. While most tests of fusion only provide a high-contrast display, a low-contrast display should be included in order to test for the breakdown of fusion under marginal conditions.

SUMMARY AND CONCLUSIONS

Selection of tests that are intended to predict the performance of the visual system under certain conditions should be based on the expected tasks to which the visual system will be exposed under those conditions. In other words, the test should be relevant to the task. Some of the tests enumerated in the previous pages were selected with only casual relationships to the aerospace visual environment or requirements. Perusal of the literature and discussions with visual scientists, research psychologists, engineers and operational aircrew yield the following "axioms:"

- No single metric of visual performance exists. The search for such a metric will be as fruitful as the search for the Holy Grail.

- No single vision test device available today is completely suitable for testing all elements of aircrew vision, either in a clinical or research environment.

- In order to construct a device that will adequately predict the visual performance of aircrew, both their visual tasks and environment must be fully described in a manner suitable for translation into hardware.

- Construction of an appropriate vision test device for aircrew will involve both modifying existing test methods and creating/validating new ones. If a single device is desired, interactive trade-offs must be made to resolve engineering incompatibilities.

- Part-task test devices need to be constructed and validated under laboratory conditions. Part of the validation will involve determination of visual performance under flight conditions.

- The optimal instrument for testing under laboratory conditions will not be optimal for clinical use. The clinical instrument will probably yield readings which are too "gross" for the vision researcher.

- Methods selected for the final test battery should be easily defensible from science and applications viewpoints. Standards, on the other hand, can be selected on two bases -- psychophysical performance specifications (medical) and the availability of a suitable resource pool (personnel). An audit trail should exist to indicate which group (medical or personnel) was responsible for the selection of individual standards, so modifications can be made as conditions change. All too often, standards, once chosen, are embedded in concrete, even though they were the result of negotiated agreements based on (then) existing conditions.

In light of these findings, we recommend modifying the Navy's proposed "Design Objectives for a Second Generation Automated Vision Testing System" to more accurately portray the use to which it is to be put. If it is to be a clinical instrument for determining visual performance of aircrew candidates, only those tests which are later proven to have a correlation with flying performance should be chosen. If it is to be a research instrument to help measure various visual parameters as candidates for a performance-based test, the existing "Design Objectives" should be amended to include testing the following likely parameters:

Disc (Blackwell) or Spot (Gaussian) detection for various izes (spatial frequencies) and contrasts. This may well be an xcellent predictor of visual detection of air-air targets under any conditions.

Color vision, using a CRT as a stimulus. The stimulus aturation as well as ambient illumination should be controlled ver a very wide range, from bright sunlight to equivalent ighttime luminances. The effects of simulated sunglasses or ther eye protection filters should also be evaluated. This ill indicate the relative performance using modern color CRT isplays.

Vergences, (adduction and abduction) using variable prisms. f phorias are adequately compensated by vergences, diplopia eed not occur under various conditions of stress. Vergences lso predict the ability of the visual system to regain single imultaneous binocular vision after experiencing diplopia. In ddition, if it is important to determine the pilot's ability to void diplopia, an alternate solution to fusion is available -- hat of suppression. Although foveal suppression prevents tereopsis, it is of higher survival value than diplopia, and ill probably remain unnoticed by the pilot. In this case, uppression might be advantageous.

Night vision should also be tested. There is currently no ight vision test that relates to night flying operations such s refueling, formation flying or target detection. AFAMRL tudies show significant differences in night vision performance etween pilots and navigators.

Manual pursuit tracking, or the ability to maintain the osition of a cursor on a moving target, can be related to the ilot's ability to accurately place his HUD pipper. An eye-hand oordination test of this type may yield valuable data.

Close cooperation among clinicians, research scientists and ;trumentation engineers should insure the development of a ɛld-usable test device whose battery of tests is appropriate, ɩid and accurate.

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